



Time-Dependent Simulation of Electrochemical Machining Under Ideal and Non-Ideal Conditions

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Abstract

This work discusses the development of a series of simulations of the Electrochemical Machining (ECM) process. The ECM process is a non-conventional manufacturing technique that is used to machine metallic materials that are prohibitively hard to shape using contact techniques. Owing to the numerous interdependencies of different process parameters, the aspects of process set-up and tool design are often based on trial and error testing. In an effort to make the ECM process more appealing for industrial use, through the reduction of costs associated with the implementation of this method, this work introduces a simulation based on the finite-element method that allows a time-dependent analysis of the machining process.

Following on from the development of an initial two-dimensional simulation, a number of different industry specific applications are presented. These include the machining of non-flat workpieces, machining using A.C. supply, and a simulation of a non-equilibrium turbine blade set-up that uses a combined tool configuration. Towards the end of this work the industrial applicability of this simulation work is progressed further into three-dimensions. For each of these industry specific adaptations, sample results are presented.

In addition to these adaptations, a section of this work discusses the development of a non-ideal, time-dependent simulation of ECM. Based on the findings of experimental work using a unique ultrasound system, this involves the introduction of a parameterised overpotential model. The increased accuracy gained from introduction of this model is then assessed through comparison with experimental data.

Declaration

I declare that this thesis has been composed by myself and except where otherwise stated the work contained herein is my own. The exception to this is the work of a fellow member of the ECM group at The University of Edinburgh, Dr. Rachel Muir, who contributed the experimental data that was used in Chapters 5 and 6.

David Curry.

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The author would like to dedicate this work to the memory of his grandfathers

Richard Curry and Robert Laing

“...but still try, for who knows what is possible...”

Michael Faraday

Nomenclature

dh	thickness of material removed per unit time from a unit area
dt	time increment
f	feed rate
h_s	maximum scallop height
i_N	workpiece node points
j	boundary ID number
m	mass
n	valency
n_s	number of scallops along the workpiece profile
t	time
x, y	space co-ordinates
x_N, y_N	x-y coordinates of workpiece node points
z	inter-electrode gap
z_0	starting gap
z_e	equilibrium machining gap
A and B	parameterised overpotential model constants
A_M	atomic mass
F	Faraday's constant (= 96,500 C mol ⁻¹)
I	current
J	current density
nJ	normal of the current density
M	number of boundary segments required to represent the workpiece surface
N	number of points required to represent the workpiece surface
V	applied voltage
V_0	overpotential
U	flow rate
ε	chemical equivalent
κ	conductivity
ρ	density
Γ_j	boundary section
η_w	overpotential at the anode

η_T	overpotential at the cathode
θ	angle
Ω	subdomain
$\psi\text{-}\varphi$	potential-flux co-ordinate system

Contents

Chapter 1: Introduction to Electrochemical Machining:.....	7
1.1 Overview	8
1.2 The ECM Process in Industry	10
1.3 Challenges to ECM in Industry.....	11
1.3.1 Process set-up challenges.....	12
1.3.2 Tool design challenges.....	13
1.4 Aims and Objectives of the thesis.....	14
Chapter 2: Background of Electrochemical Machining:.....	16
2.1 Introduction.....	17
2.2 Advanced Metal Alloys, Their Properties and Applications	17
2.2.1 Ferrous Alloys.....	18
2.2.2 Non-ferrous Alloys.....	19
2.3 Machining Super Alloys	21
2.3.1 Conventional Machining Techniques	21
2.3.2 Non-Conventional Machining Techniques	22
2.4 Electrochemical Machining	28
2.4.1 Overview of the ECM process.....	28
2.5 Theory of ECM	30
2.5.1 Die-Sinking ECM using Flat Electrodes.....	30
2.5.2 Variations during ECM.....	33
2.6 ECM Variants	35
2.6.1 Combined tool machining.....	35
2.6.2 Ball-ended/universal electrodes	36
2.6.3 Electrochemical Drilling	37
2.6.4 Sub-sea defect analysis and repair	38
2.7 Improving the Industrial Application of the ECM Process.....	40
2.8 Tool Design Methods.....	40
2.9 Simulation of the ECM process	45
2.9.1 Analytical Techniques.....	45
2.9.2 Numerical Techniques	46
2.9.3 ECM Simulation under Non-ideal Conditions.....	48
2.9.4 Simulation of ECM variants	49
2.9.5 ECM Simulation Software	50
2.10 Conclusion	51
Chapter 3: Developing a Time-Dependent Simulation.....	52
3.1 Introduction	53
3.2 Commercial Packages vs. Self-Programmed	53
3.3 Moving boundary FEA	54
3.4 Pre-processing Requirements.....	55
3.4.1 Defining Input Parameters	55
3.4.2 Defining Geometry.....	57
3.4.3 Creating a movable boundary	58
3.4.4 Defining FEA conditions	61
3.4.5 Additional set-up processes.....	62

3.4.6	Defining the FEMLAB Data Structure	62
3.4.7	FE Analysis	63
3.5	Processing Requirements	66
3.5.1	Data extraction	66
3.5.2	Calculating material removal	68
3.5.3	Movement of workpiece boundary	68
3.5.4	Updating FEMLAB structure.....	70
3.5.5	Simulation status display	71
3.5.6	Evaluating completion	72
3.6	Post-processing Requirements	74
3.7	Simulation Flowchart	75
3.8	Verification of Simulation: Machining a flat workpiece with double-cosine tool	76
3.8.1	Simulation Overview	76
3.8.2	Results	77
3.9	Conclusions	79
Chapter 4: Industrial Applications of the Simulation		81
4.1	Introduction	82
4.2	Machining non-flat workpieces.....	83
4.2.1	Modifications required	84
4.2.2	Setting up a rough workpiece simulation.....	85
4.2.3	Sample Results	88
4.3	Alternating Current ECM.....	91
4.3.1	Modifications required	91
4.3.2	Small time-step (STS) approach	92
4.3.3	Large time-step (LTS) approach	94
4.3.4	Choice of method	97
4.4	Combined tool ECM	98
4.4.1	Modifications required	98
4.4.2	Example Simulation	103
4.5	Conclusions	105
Chapter 5: Developing a Non-Ideal ECM Simulation Part A.....		106
5.1	Introduction	107
5.2	Overpotential	107
5.3	Ultrasound ECM Set-up	108
5.4	Ultrasound Measurement Theory	111
5.5	Chronoamperometric Theory	112
5.6	Comparing the Ultrasound and Chronoamperometric Methods	114
5.6.1	Ultrasound Results	115
5.6.2	Chronoamperometric Results	117
5.6.3	Detailed Chronoamperometric Analysis	118
5.7	Investigating the Trends in Overpotential during ECM.....	120
5.7.1	Experimental details.....	120
5.7.2	Results	121
5.7.3	Trends in I vs. V_0 data.....	124
5.8	Conclusions	127

Chapter 6: Developing a Non-Ideal ECM Simulation Part B	128
6.1 Introduction	129
6.2 Integrating a parametric overpotential model	129
6.3 Modifications required to the simulation	132
6.3.1 Input of the required model parameters	132
6.3.2 Translation of $I-V_0$ relationship to $J-V_0$ relationship	133
6.3.3 Calculation of initial V_0 condition	133
6.3.4 Inclusion of time-dependent variation calculation into the iterative solver	134
6.3.5 Post-Processing modifications	135
6.4 Sample simulation	136
6.4.1 Experimental Set-up	136
6.4.2 Simulation Set-up	136
6.4.3 Results and Discussion	138
6.5 Conclusions	141
6.6 Non-ideal Simulation Using a Non-Flat Tool	142
6.6.1 Modifications required	142
6.6.2 A Comment on the Implementation of This Method Using the Current System	145
Chapter 7: Three-Dimensional ECM Simulation	146
7.1 Introduction	147
7.2 Modifications required	147
7.2.1 Establishing 3-D FEA conditions within FEMLAB	148
7.2.2 Creating a suitable workpiece boundary surface	149
7.2.3 Identifying the boundary geometries	150
7.2.4 Extraction of data from the workpiece surface	151
7.2.5 Implementing workpiece boundary movement	151
7.2.6 Reforming a suitable geometry	151
7.3 Example Simulation	154
7.3.1 Simulation Set-up	154
7.3.2 Results	155
7.4 Conclusions	157
Chapter 8: Conclusions and Further Work	158
8.1 Conclusions	159
8.2 Further Work	160

List of Figures

Figure 1: Simple schematic of the ECM process	8
Figure 2: The evolution of the workpiece; (a) at the start of machining, (b) at equilibrium	9
Figure 3: The 360 degree ECM system (image from Clifton [3])	11
Figure 4: The chip production technique of conventional metal cutting	21
Figure 5: Simple schematic of the EDM process	24
Figure 6: Schematic of the laser beam machining system	25
Figure 7: Schematic of electron beam machining	26
Figure 8: Schematic of the electroplating process	27
Figure 9: Simple schematic of electrolysis	28
Figure 10: The planer ECM system. In this system f is the feed rate, z is the inter-electrode gap, and dh is the thickness of material removed per unit time from a unit area of the workpiece.	30
Figure 11: A breakdown of the overpotential during electrolysis.....	34
Figure 12: Combined tooling, both sides of the workpiece are machined simultaneously	35
Figure 13: Overview of a ball-ended tool machining a workpiece.....	37
Figure 14: Schematic of the electrochemical drilling technique.....	38
Figure 15: Images taken showing the sample removed from a pipe, and the tool used for the operation (image taken from [3]).....	39
Figure 16: The $\cos-\theta$ method of tool design (adapted from Oliver [1]).....	41
Figure 17: The two co-ordinates systems used by Alder [46]: (a) the physical coordinates; (b) the $\psi-\phi$ coordinates	42
Figure 18: Schematic of a sample tool and workpiece geometry	57
Figure 19: Corresponding ECM simulation geometry	57
Figure 20: Distribution of 100 starting points along the workpiece boundary	58
Figure 21: A generic example demonstrating the boundary ID numbering system in FEMLAB	59
Figure 22: Flowchart describing the algorithm for determining connectivity between boundary sections.....	61
Figure 23: The boundary and subdomain conditions used in the ECM simulation ...	61
Figure 24: The data structure allows information to be passed between the simulation code and the FEMLAB software.....	62
Figure 25: Meshed subdomain including detail section taken from a geometry midway through an ECM simulation. This typical mesh consists of 5,000 elements	64
Figure 26: Diagram showing the calculated electric field using a stream-lined representation	64
Figure 27: Flowchart of the processor algorithm ('WP' = workpiece).....	66
Figure 28: Sample graph showing the spline function of the current density along the workpiece	67
Figure 29: Diagram demonstrating how the effect of point cross-over can result in unphysical geometries	69
Figure 30: Equal distribution of points along the workpiece boundary based on arc-length.....	70

Figure 31: Sample output display to the user whilst the simulation is running. The top window shows the status of the geometry, the lower window is a plot of the current transient.....	73
Figure 32: Flowchart describing the current based exit condition	74
Figure 33: Flowchart describing the entire algorithm used for the time-dependent simulation of ECM ('WP' = workpiece)	76
Figure 34: Output display from the machining to equilibrium of an Inconel 718 workpiece.....	78
Figure 35: The evolution of the workpiece boundary (time in seconds).....	78
Figure 36: Comparison of simulated (==) and experimental (---) workpiece profiles at equilibrium.....	79
Figure 37: The location of 5 measurement points where workpiece thickness was determined.....	80
Figure 38: Graph showing the material removal comparison between experimental (□) and simulation (□) results.....	80
Figure 39: Deviation between simulation and experimental material removal results at the 5 measurement locations	81
Figure 40: Rendered images of a scalloped and finished turbine blade.	84
Figure 41: A semi-random workpiece generated using a function within the pre-processor	85
Figure 42: Starting gap (z_0) for a flat and a scalloped workpiece	86
Figure 43: Area indicated is the region of the workpiece surface scanned using the ZYGO machine. The resulting surface topography is shown below.....	87
Figure 44: Cross-section of the height map	88
Figure 45: Starting geometry profile for the scallop simulation	88
Figure 46: The full length scalloped workpiece.....	90
Figure 47: Detailed view of a 10 mm section of the workpiece	90
Figure 48: Machining of the scalloped workpiece surface as it approaches a flat tool	90
Figure 49: Total material removal over time for the machining of a scalloped workpiece.....	91
Figure 50: Current transient for A.C. pulse simulation	94
Figure 51: Variation in gap width over time when machining using A.C.....	95
Figure 52: Comparison of variation in gap width over time for a D.C. and A.C. simulations using a flat workpiece	97
Figure 53: Cross-sectioned view of an aerofoil blisk undergoing combined tool ECM	99
Figure 54: Sample geometry used in the simulation	100
Figure 55: Arrangement of points along workpiece boundary	102
Figure 56: The evolution of the tools and workpiece during combined tool simulation (t in seconds)	105
Figure 57: Image of segmented tool, inset is of underside view of segment connections.....	110
Figure 58: Schematic diagram of the ECM system with the ultrasound probe.	111
Figure 59: Schematic of planar tool and workpiece set-up (a) before steady state current, equilibrium (b) at steady state current. Relative movement of electrodes is shown by arrows and distance between electrodes by double-headed arrows	114

Figure 60: Typical time-resolved plot of the variation in interelectrode machining gap (ooo) and overpotential (==) against time during ECM.....	116
Figure 61: Plots of variation in n against t , $p = 11$ shown in grey and $p = 50$ shown in black.....	117
Figure 62: Comparison of time-resolved ultrasound $I-V_0$ data and global I-analysis, z -analysis data (shaded regions).....	118
Figure 63: Comparison of time-resolved $I-V_0$ data and detailed I ($\square$) and z -analysis ($\diamond$).....	119
Figure 64: Typical current transients for segments 1-7. The current observed for each segments 1 to 7 are indicated and marked I_1 to I_7 ($\Rightarrow$); the time dependent behaviour of the end segment currents I_1 and I_7 are similar, but different from I_2 to I_6 ($\Rightarrow$). The approach, retract and re-approach phases are indicated in this and subsequent plots for clarity. Also shown is the z - time data ($\Rightarrow$) derived from the ultrasound measurements.....	122
Figure 65: The corresponding calculated time-resolved n data for $p=11$ ($\Rightarrow$) and $p = 50$ ($\Rightarrow$) for the experiment in Figure 8.....	123
Figure 66: The corresponding V_0 data for the experiment in Figure 64 as a function of time	124
Figure 67: Approach (xxx), retract (xxx) and re-approach (xxx) $I-V_0$ data for the $z_0 = 2.960$ mm data.....	124
Figure 68: Typical $I-V_0$ data for the electrochemical dissolution of J with $z_0 = 1.055$ mm and an electrolyte concentration of 12% (xxx), and $z_0 = 2.960$ mm and an electrolyte concentration of 15% (xxx). Also shown are theoretical lines calculated from Equation 22 with the appropriate electrolyte conductivities of $\kappa = 0.184$ S cm ⁻¹ and $\kappa = 0.210$ S cm ⁻¹ respectively.	126
Figure 69: An $I-V_0$ graph for the machining of SS410 at 8 V in NaCl.....	131
Figure 70: The linear fit through the $I-V_0$ data.....	132
Figure 71: $I-V_0$ plot recorded during machining of actual Titanium workpiece.....	138
Figure 72: Comparing the $I-V_0$ trend for both experimental ($\circ$) and simulation ($\circ$) data.....	139
Figure 73: Comparison of z for experimental (---), non-ideal simulation ($\Rightarrow$) and ideal simulation (ooo).....	140
Figure 74: Calculated V_0 plotted against time for the non-ideal simulation.....	141
Figure 75: A single boundary segment in the ECM simulation.....	145
Figure 76: Image of a meshed sample geometry.....	149
Figure 77: A sample geometry (a) before boundary gridding, (b) after gridding (resolution was defined as 10x25).....	150
Figure 78: The cutting plane required to form the new workpiece surface and the extended geometry to be cut	153
Figure 79: Removal of the lower subdomain section results in the geometry to be used for subsequent analysis	154
Figure 80: Isometric view of the half ball starting geometry.....	155
Figure 81: Side and top views of the input geometry (all dimensions in mm).	155
Figure 82: The 3-D ECM simulation geometry at 4 stages during machining (t in seconds).....	157
Figure 83: Surface map of the workpiece geometry at $t=800$ secs. The surface is coloured by material removal.....	157

Chapter:

1 Introduction to Electrochemical Machining

This chapter begins with an introduction to the electrochemical machining process. It presents a brief history of the method and introduces the advantages and challenges to the industrial application of the technique. With these challenges as the motivation, the chapter finishes by stating the aims of this research, followed by a chapter-by-chapter overview of the thesis.

1.1 Overview

Electrochemical machining (ECM) is a non-contact manufacturing technique based on the principals of electrolysis. The main use of the process is in the machining of hard metallic alloys, for example titanium or Inconel, whose material properties mean it is difficult to shape these metals efficiently using traditional, contact techniques.

This thesis will primarily be referring to a form of ECM known as die-sinking ECM. In this variant of the process a tooling electrode (the cathode) and a workpiece electrode (the anode) are positioned in a high-pressure cell and an electrolyte is pumped through the inter-electrode gap. Commonly used electrolytes include sodium chloride (NaCl), sodium nitrate (NaNO_3), and potassium chloride (KCl).

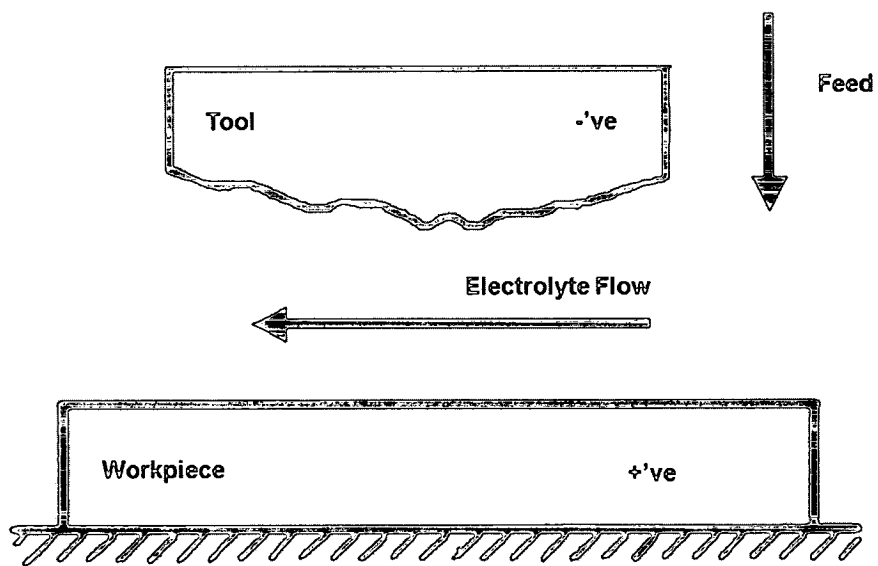


Figure 1: Simple schematic of the ECM process

During the process, a current is applied across the inter-electrode gap and the two electrodes are fed closer together. Dissolution takes place at the surface of the workpiece, with the material removal rates proportional to the current density at the

workpiece surface [1]. The electrolyte is continually pumped between the electrodes to remove the by-products of the dissolution process (dissolution debris, hydrogen) from the machining area as well as to try and sustain a constant electrolyte temperature throughout machining. In many cases if machining is sustained for a sufficient period an 'equilibrium' state is reached. At this stage, the rate of material removal at the workpiece becomes constant and the workpiece shape is invariant (Figure 2).

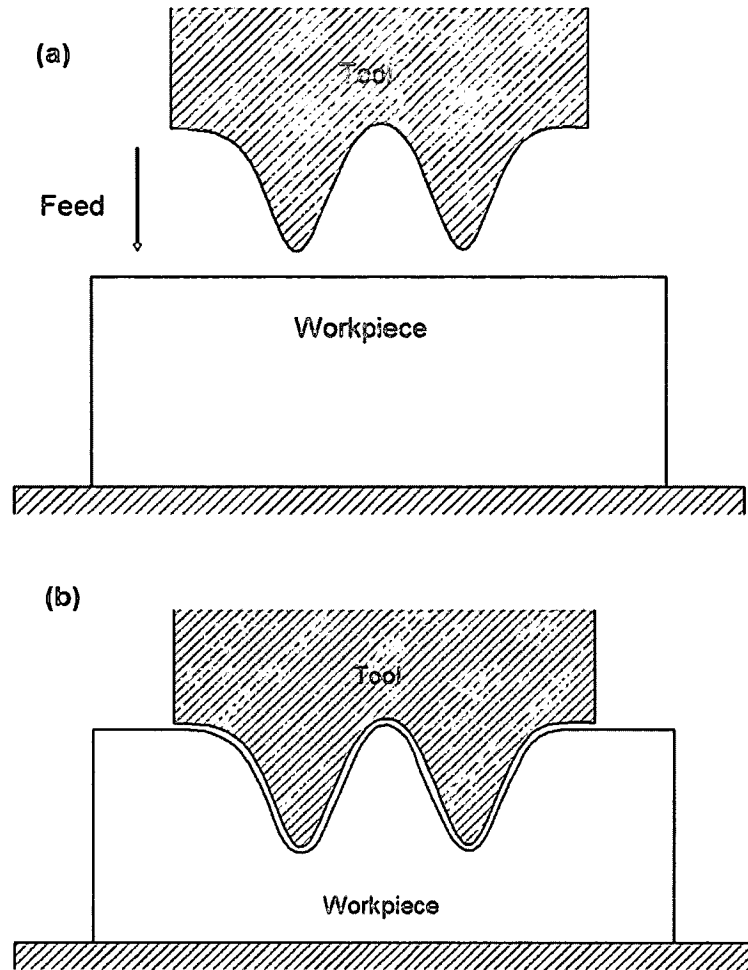


Figure 2: The evolution of the workpiece; (a) at the start of machining, (b) at equilibrium

The actual origin of ECM in industry is subject to debate, but the process is based on the principals of electrolysis. This electrochemical phenomenon has been subjected to scientific investigation since its discovery by Michael Faraday in

1834. The intentional electrolytic removal of material has also been implemented for a long period of time, in the form of processes such as electropickling, where an electrolytic solution is used to remove blemishes such as oil marks from sheet steel. This process was then extended into more controlled electrolytic fabrication techniques such as electroplating. The advances made in material science, namely the development of high-strength alloys, soon made it increasingly expensive to fabricate products using conventional, contact machining techniques. With these new materials proving increasingly useful, due to a strength-to-weight ratio and corrosion resistance levels previously unseen, the development of electrochemical methods has advanced to a level where they can be deployed as viable manufacturing techniques. Today, a variety of products are manufactured using this technique, from turbine blades and blisks in the aerospace industry, to microelectronics components, to razor blades and medical equipment.

1.2 The ECM Process in Industry

There are many advantages to the ECM process as a method for fabricating parts that make it an attractive technique for manufacturing industries. Provided the material being machined is conductive, the process will machine regardless of material hardness. This makes it a very powerful and attractive option for the machining of superalloys. Secondly, due to the non-contact nature of the process, the tool can be made from a softer material than the workpiece and experiences no wear. Typical tool materials include copper, stainless steel, and brass, though copper is the usual choice owing to its resistance to corrosion, ease of manufacture and high conductivity [2]. Unlike conventional, contact machining techniques, ECM does not introduce additional stresses in the final workpiece. The actual machining process is also comparatively quick when compared to conventional techniques.

ECM has been used in a variety of industries since the 1950s. Originally developed to aid the manufacture and sharpening of carbide-tipped drills [1], the technology spread to a variety of industrial sectors. Variants of the process have developed that allow operations such as deburring, grinding, milling and drilling to be performed.

As the technology has become more widely used more advanced machining approaches have been developed. In the aerospace industry, Rolls Royce Ltd. were responsible for the first fully automated compressor blade production facility, known as 360° ECM [3]. Developed in 1978 [4], this process is one of the most advanced applications of ECM. The 360° ECM compressor blade production facility allows the machining of both the convex and concave sides of a turbine blade simultaneously (Figure 3) to specifications previously unattainable with earlier methods.

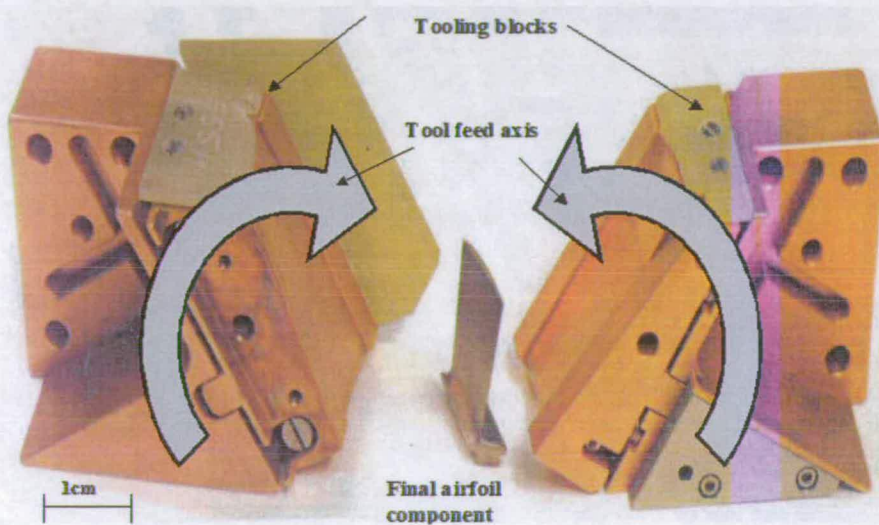


Figure 3: The 360 degree ECM system (image from Clifton [3])

Through automation of the machining process, the 360° ECM process is able to produce titanium and nickel turbine blades at a rate of 2,500 per week.

1.3 Challenges to ECM in Industry

Though the ECM process has been used in certain industries for some time, it is not a widespread manufacturing technique owing to a number of aspects of the process that prove undesirable and in some cases, costly. Consequently many manufacturing companies who could benefit from using ECM prefer to rely on traditional, contact methods. Partly this is due to the expensive set-up costs of an ECM system, partly to the lack of expertise and knowledge in determining suitable

machining set-ups, and partly due to time and effort required to design suitable tools. Whilst the cost of establishing an ECM manufacturing process are likely to remain relatively large due to the nature of the high pressure system, a large body of research exists, and is discussed in more depth in Chapter 2, that has attempted to provide a clearer understanding of the process, and reduce the costs associated with ECM tool design.

Research has focused on a number of different aspects of machining, from experimental investigations into the behaviour of the various parameter changes that take place during ECM, to computational techniques designed to simulate the process or provide direct tool design. This research has provided industry with a useful catalogue of information regarding the ECM, though still there is insufficient information to categorically define the process information for all systems.

1.3.1 Process set-up challenges

The success of an ECM process is dependent upon a number of different parameters and their interactions. Even prior to machining set-up requirements, establishing a suitable ECM process can prove financially costly. This is due to the specialised equipment required for suitable control systems, high pressure equipment (Wilson gives a range of 5 to 27 bar [2]), and electrolyte treatment and storage facilities. The specific manufacturing requirement to be fulfilled may also require a unique machining set-up to produce satisfactory results. Once the ECM system has been established further costs arise from the power consumption required to run the operation as well as the environmental impact to be considered. Once the electrolyte has been used during machining it will be contaminated with the by-products of the electrolytic process, and subsequently needs to undergo a filtering and decontamination process before it can be disposed of.

With the machine set-up in place the next issue is with the calibration and implementation of a capable manufacturing process. An efficient and cost effective ECM process is principally dependent upon ensuring a suitable initial parameter set-up [5]. Examples of critical parameters are feed rate, applied voltage, and electrolyte flow-rate [6-9] and pressures [10]. Even small changes in each of these

will result in variation in the machining process. Beyond these concerns, further set-up decisions, for example electrolyte type or D.C. or A.C. current supplies, all have an effect on the process parameters and their effects need to be examined closely.

In addition there is the dissolution process itself. The electrochemical dynamics are complex and there are interactions between numerous parameters, at both a macroscopic (dissolution debris, hydrogen formation) and atomic level (ion migration, oxide films) all having an effect on the performance of an ECM system [11, 12]. All of these issues can result in a time consuming process of trial-and-error to ensure that the correct parameters are achieved, with potentially many iterations required before a balance is found that allows for the most efficient machining possible. Even for the most experienced ECM operator it can be challenging to establish the correct process set-up to produce the required final workpiece.

1.3.2 Tool design challenges

Following on from the difficulties of establishing a suitable process set-up is the problem of designing a suitable tool to produce the required workpiece following machining. The parameter variations discussed above will cause geometric deviations from a tool shape suggested by an idealised theory of the process. Of particular importance is the impact these variations have on the electrolyte conductivity [13] which is critical in determining the material removal from the workpiece. Consequently, the design of a tool can be based on a reactive, intuitive approach, often with a trial-and-error approach being taken to compensate for these effects.

1.4 Aims and Objectives of the Thesis

Despite the challenges of the process, there is still an interest within industry to use the technology in order to benefit from the long-term savings gained from the lack of tool wear, and speed of manufacture available. A good deal of research has been made in both the fields of Engineering and Chemistry to try and reduce or remove the trial-and-error aspects of the process.

With the overall goal of adding to the existing techniques and knowledge currently available, the aims of this research are:

- The production of a time-dependent simulation of the electrochemical machining process in both 2-D and 3-D.
- Assessment of the applicability of this simulation to industry by investigating specific adaptations of the ECM process, including machining under non-equilibrium conditions and machining in three dimensions.
- Characterisation and inclusion of a critical process parameter, the overpotential, into a simulation of the ECM process.
- Validation of the resulting non-ideal simulation through comparisons with results obtained from experimental work and also an ideal-simulation.

This thesis is an extension to existing studies performed at Edinburgh University. Experimentally, the unique ultrasound system developed by D.Clifton and utilised by R.Muir in her characterisation work allowed for the development of the parameterised model of the overpotential. Although ECM simulation work has been performed by Alder and McClennan, this was largely analytical and related primarily to tool design. Subsequently the time-dependent simulation using the numerical methods outlined in this work is the first time such a method has been implemented within the ECM group at Edinburgh University.

The work of the thesis is presented in the following form:

Chapter 2 begins by discussing the increasing need for non-conventional manufacturing techniques in the fabrication of parts made from superalloys. It then goes on to discuss the theory behind the ECM process, and presents efforts by others to reduce the need for trial-and-error tool and process design. Chapter 3 then presents the methodology used in the development of, and results obtained from, a time-dependent, finite-element based, simulation of the machining process under ideal conditions. This work leads on to Chapter 4 where this simulation has been adapted and changes introduced to represent a number of industrially applicable ECM manufacturing techniques. The motivation for this work was the requirement to simulate specific machining issues experienced by Dutch Aero (formally Philips Aerospace).

Chapters 5 and 6 form a study in the further advancement of the simulation by introducing a parameterised model of the overpotential. This work was the basis of a conference paper presented by the author, and a journal paper accepted for publication by the IMechE. Chapter 5 presents the methodology and results of experimental work using a unique ultrasound measurement system to produce time-dependent overpotential values. The behaviour of the overpotential and its dependence upon the current is discussed, before concluding that this relationship can be exploited for use in a non-ideal, time-dependent simulation. Chapter 6 introduces this model into the existing simulation. Through comparisons between experimental and ideal simulation data, the impact of using the parameterised overpotential model is assessed. This chapter also discusses the variation in methodology required to introduce such a parameterised model into simulations of non-flat workpieces.

Finally, Chapter 7 presents a further adaptation of the simulation, a three-dimensional, time-dependent simulation of ECM. Again, this has been developed with industrial applications in mind. The methodology is discussed and results obtained through simulation are presented.

Chapter:

2 Background of Electrochemical Machining

This chapter is a presentation of the need for, the theory behind and the work based upon the ECM process. Advanced alloys, conventional and non-conventional machining techniques are discussed with a view of putting ECM into context. The planar theory of ECM is presented, followed by a review of techniques developed to reduce the trial-and-error involved in many aspects of establishing an efficient ECM system.

2.1 Introduction

Demand in industry to produce parts that are light, strong and corrosion resistant has led to the development of more advanced metal alloys, and super alloys. These advanced materials are used in a number of manufacturing sectors and often in the fabrication of parts where accuracy is paramount. Owing to the high strength of these materials – one of the characteristics that make these materials so desirable - conventional contact-based machining techniques often used to form these metals can be expensive and time consuming. This chapter introduces alternative techniques developed that have been specifically designed with the manufacture of these materials. In particular the theory, application and state of the art of the electrochemical machining (ECM) process will be discussed.

2.2 Advanced Metal Alloys, Their Properties and Applications

Advanced metal alloys are utilised in a number of industrial sectors, ranging from use in sub-sea pipelines and turbine blade production to jewellery. From an engineering point of view, the desire to manufacture parts that were both light and tough fuelled the development of these alloys. The most advanced of these metal alloys have been termed ‘superalloys’ and are often used in ‘hot’ environments. There are two principal qualities a material must have if it is to be used successfully at high temperatures, high resistance to oxidation and high strength. These super alloys display much greater strength properties at high temperatures (815-1098°C) than conventional alloys [14]. These are usually based on nickel (Ni), cobalt (Co) or iron (Fe). Through the addition of other elements, the properties of these metals can be enhanced. The addition of chromium (Cr), for example, enhances the corrosion resistivity of a metal, whilst molybdenum increases its strength and reduces creep. In general conventional machining almost all grades of super alloys are cast, though a small number are wrought [14].

In general these metals can be split into two groups, ferrous metals and non-ferrous metals depending on the quantity of iron that makes up their composition.

2.2.1 Ferrous Alloys

Ferrous alloys are alloys that display a high Fe content. Whilst Fe will oxidise readily when exposed to oxygen, the addition of at least 10% Chromium into the alloy will provide a barrier preventing the corrosion of the metal. Typical ferrous alloys that are used in industry are forms of stainless steel. There are a number of different types of stainless steel and the uses vary from domestic fittings to jet engine parts and sub-sea devices.

In this work, two stainless steels will be used in the context of ECM experiments – SS410 and Jethete.

SS410

SS410 is martensitic stainless steel that offers the high strength and wear resistance as well as corrosion resistance. Table 1 shows the composition of SS410.

Table 1: Composition of SS410

<i>Element</i>	<i>Fe</i>	<i>Cr</i>	<i>Ni</i>	<i>Mo</i>	<i>Mn</i>	
<i>% by atomic mass</i>	85.5	12.75	0.23	0.01	0.72	
<i>Element</i>	<i>Cu</i>	<i>C</i>	<i>S</i>	<i>P</i>	<i>Si</i>	<i>N</i>
<i>% by atomic mass</i>	0.08	0.14	0.02	0.04	0.49	0.02

Its strength, toughness and wear properties derive from the compositional addition of carbon, whilst chromium provides corrosion resistance. Applications of SS410 include cutlery, screws, rifle barrels and parts within jet engines [15].

Jethete

Jethete (also known as Alloy 190, M190) is a stainless steel of martensitic structure that is applied in the aerospace industry. It’s composition includes a relatively high nickel content providing additional strength and molybdenum that provides

additional corrosion resistance, especially against pitting and crevice corrosion. It is used in applications that require:

- High static and fatigue strengths, under both instantaneous and dynamic loadings.
- Adequate toughness to withstand shock loads.
- Sufficient stiffness to reduce deformation.
- High hardness to prevent contact fatigue.
- Adequate resistance to corrosion and stress cracking.
- Resistance to temperatures up to 400°C.

As a result typical applications include the turbine blades, jet engine components such as gears and bearings, medical implants for example hip replacements, and sub-sea piping and valves. The composition of Jethete is shown in Table 2.

Table 2: Composition of Jethete

<i>Element</i>	Fe	Cr	Ni	Mo	Mn	Cu
<i>% by atomic mass</i>	80.63	12.5	3.0	2.0	0.90	0.40
<i>Element</i>	C	S	P	Si	N	V
<i>% by atomic mass</i>	0.13	0.02	0.03	0.35	0.04	0.40

2.2.2 Non-ferrous Alloys

Non-ferrous alloys consist of a group of alloys that have a low, or zero, iron content. In this work two non-ferrous alloys will be referred to, titanium 6-4 and Inconel 718.

Titanium 6-4

This is the most widely available and heavily used grade of titanium alloy. Owing to the high melting point of titanium (1668°C) components fabricated using this material are suitable for use in ‘hot’ environments e.g. turbine blades for compressors [16]. Other uses, such as internal structures in aircraft and spacecraft,

exploit the low density and high specific strength of this alloy [17]. It is highly corrosion resistant and consequently can be used in a variety of environments including marine applications [18].

Table 3 shows the composition of titanium 6-4.

Table 3: Composition of titanium 6-4

Element	<i>Fe</i>	<i>Ti</i>	<i>Al</i>	<i>C</i>	<i>O</i>	<i>N</i>	<i>V</i>
% by atomic mass	0.17	89.91	5.89	0.01	0.15	0.02	3.76

One limitation of this material is that at high temperatures titanium can react with other materials at high temperatures [14].

Inconel 718

This nickel-based alloy is corrosion resistant and, due to the addition of niobium, it offers good strength at high temperatures [19]. Consequently it is used to fabricate components for high temperature sections of gas turbines [20]. It is also used for tooling, nuclear reactors and rocket motors. Table 4 shows the composition of Inconel 718.

Table 4: Composition of Inconel 718

Element	<i>Fe</i>	<i>C</i>	<i>Mn</i>	<i>Si</i>	<i>P</i>	<i>S</i>	<i>Ni</i>	
% by atomic mass	12.28	0.08	0.35	0.35	0.015	0.015	54.0	
Element	<i>Co</i>	<i>Cr</i>	<i>Al</i>	<i>Mo</i>	<i>Ti</i>	<i>B</i>	<i>Cu</i>	<i>Ta</i>
% by atomic mass	1.0	21.0	0.08	3.30	1.15	0.006	0.15	5.5

2.3 Machining Super Alloys

Before continuing on a more detailed look at the ECM process, this section will present details of alternative manufacturing processes that are often seen as viable competitors. Broadly speaking these can be split into two areas: conventional and non-conventional machining techniques.

2.3.1 Conventional Machining Techniques

Conventional machining techniques are based on a contact method for the removal of material. In order for this to happen efficiently the tool material must be harder than the workpiece being shaped. The tool used is usually sharp, in order to minimise the force required to remove a chip (Figure 4), though the machining tip must however be sufficiently sized so as to withstand the forces involved [21].

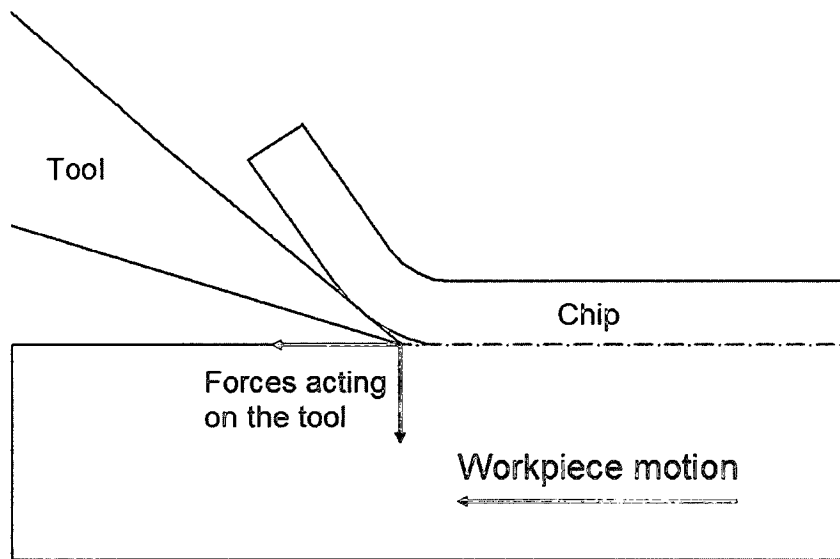


Figure 4: The chip production technique of conventional metal cutting

Due to the contact nature of this process, temperature increases at the tool-workpiece interface occur. This heating can lead to plastic deformation of the tool shape [21] and contribute towards tool-wear. In addition, the contact nature of

these methods can result in undesirable residual stresses in the final product [22]. Common tooling materials include cemented carbides, coated carbides and ceramics [21], though even the most recent tool materials have difficulty machining workpieces of a similar strength. Examples of conventional, contact-method, machining techniques include milling, grinding, turning and CNC machining [23, 24]. In many cases an initial machining run will be made to machine out the rough outline of the required workpiece shape; this will then be followed by a series of secondary machining runs, using a finer tool, to produce the desired surface finish to the product.

The increasing demand for products manufactured from higher strength alloys only serve to magnify the disadvantages of machining using contact techniques. Machining superalloys in this manner, especially when a high quantity of material removal is required, will often result in rapid tool-wear, increasing the cost of fabrication. In addition to this cost is the time required for the fabrication of parts. The process of setting up and implementing different machining patterns can be a lengthy process, especially if the part to be machined is large and complex.

With the reduction of these production costs and improvement of the integrity of the final product as the motivation, alternative manufacturing techniques have been developed that adopt an unconventional approach. In particular the need to manufacture superalloys efficiently and more cost effectively has led to the development of non-contact manufacturing techniques to drive the removal of workpiece material.

2.3.2 Non-Conventional Machining Techniques

Non-conventional machining techniques include a wide range of mechanical, electrical, thermal and chemical removal methods. These machining approaches rely on systems whereby material removal is induced through methods other than direct contact. Amongst these is ECM, however before a detailed look at the processes behind the ECM process is discussed, an overview of some alternative non-conventional machining techniques is presented.

Electro-discharge Machining (EDM)

Electro-discharge machining is a manufacturing technique that makes use of the energy generated from spark discharges to erode a metal surface. Metal erosion through spark discharge was first observed by Presitley in 1768 [25], though it was not until 100 years later that the technique was applied to engineering problems. In 1943 Lazarenkos [26] deduced that spark discharges could be used to machine new metals. In order to achieve effective machining the spark discharges need to be of a short-pulse time and of high repetition rates. This process can be used to machine any conductive material.

The spark is generated through use of an RC circuit that utilises the rapid discharge of a capacitor to produce a spark [25]. The workpiece and the tool are connected to the capacitor and submerged into a liquid dielectric to concentrate the energy onto a small area. As the capacitor charges and discharges, a flow of sparks arises. The sparks occur in the area of least resistance - usually the area of the smallest inter-electrode gap – and here the energy from the spark causes the workpiece material to melt away. Subsequent sparks then erode material from the area of the next smallest gap. The tool is advanced towards the workpiece providing continual machining of a small area (Figure 5). The dielectric serves to concentrate the discharge energy into a small cross sectional area as well as cooling the two electrodes and flushing away the debris [26].

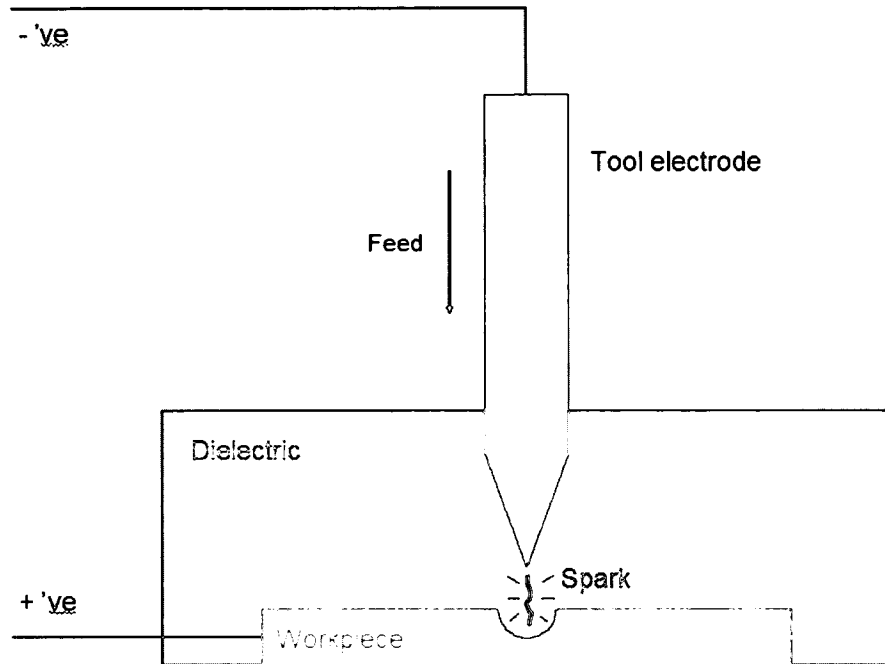


Figure 5: Simple schematic of the EDM process

EDM is a widely used manufacturing technique, and is used extensively in drilling operations. EDM has the advantage over ECM in that it is cheaper to set-up an EDM system [27], though additional costs are incurred since the tool material is also eroded by the sparking process. Though the process is slower and can result in residual stress of the workpiece [24], it predominates in die-sinking manufacturing operations.

Laser Beam Machining

Laser beam machining (LBM) is a thermal material removal process [24, 28]. Light is radiated from an excited lasing medium (such as xenon or krypton). A laser beam is focused and concentrated onto a material (Figure 6) producing heat energy in excess of 10^6W/mm^2 .

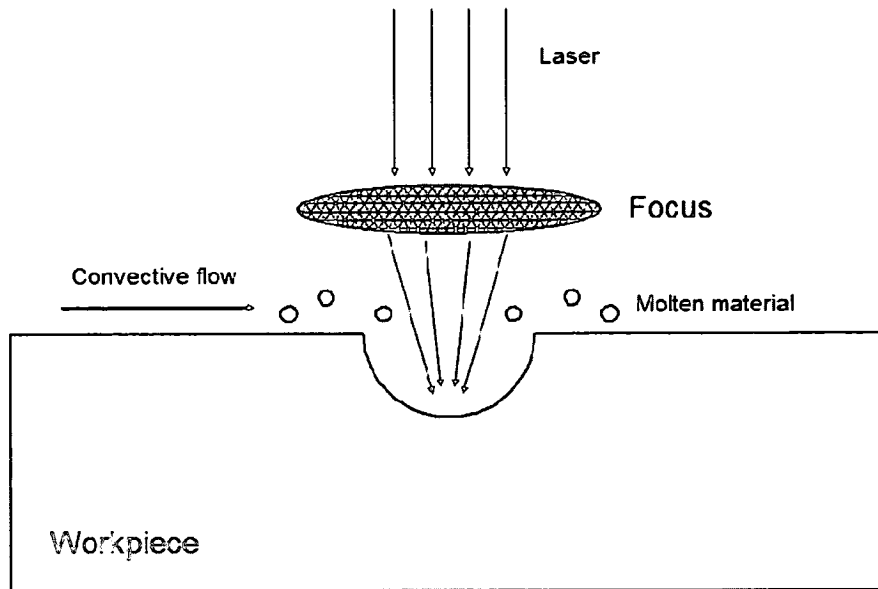


Figure 6: Schematic of the laser beam machining system

LBM produces material removal in three main forms. Firstly if the concentrated heat is focused onto a solid, the material can be machined through a process of melting. Once converted to a liquid state, the molten material can be removed either through use of convective flow, a jet of gas, or simply by gravity [28]. The second manufacturing approach is that of evaporation and can be instigated by heating the molten material to the point of evaporation. This gas or vapour can be removed from the machining area by use of a jet of gas. Finally material may be removed through a process known as 'sputtering' which can be used provided the hot vapours impart sufficient kinetic energy - enough to overcome the surface tension forces - to small volumes of liquid. These globules can be ejected from the heating zone. This final process often displaces a considerable amount of material and upon solidification can form a crater around the heated zone.

Laser manufacturing systems are becoming increasingly more popular due to advances being made in making them precise and multitasking [28]. The variety of applications of such systems includes:

- Cutting
- Drilling
- Welding – penetration and spot welding
- Surface treatments – hardening, melting, alloying, cladding
- Micro-machining

Electron Beam Machining

Electron Beam Machining is similar to LBM but uses a focused stream of electrons, accelerated by a potential field ranging from 50,000 to 200,000 volts, onto a workpiece (Figure 7) causing the workpiece material to heat up and then vaporise [25, 29]. The process needs to be carried out in a vacuum.

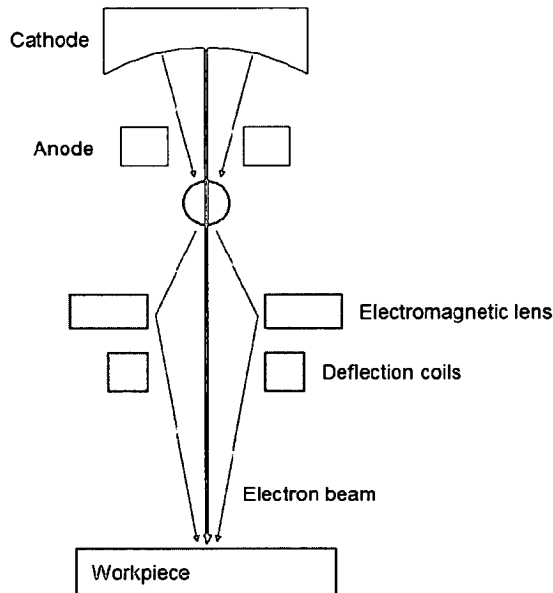


Figure 7: Schematic of electron beam machining

This technique can be applied to perform the cutting of holes or slits in a wide range of materials [25].

Electroplating

This process is a form of electroforming, where a section of material of the desired plating material is situated in an electrolyte bath with the part to be plated. An electrical circuit is established between the two parts with the workpiece set as the cathode and the plating material as the anode. As current passes through the electrolyte, a dissolution process takes place at the anode and cations of the base metal are released and then associate with anions within the electrolyte. At the cathode the cations are reduced to the base metal which then, over time, forms a coating around the workpiece (Figure 8) [30].

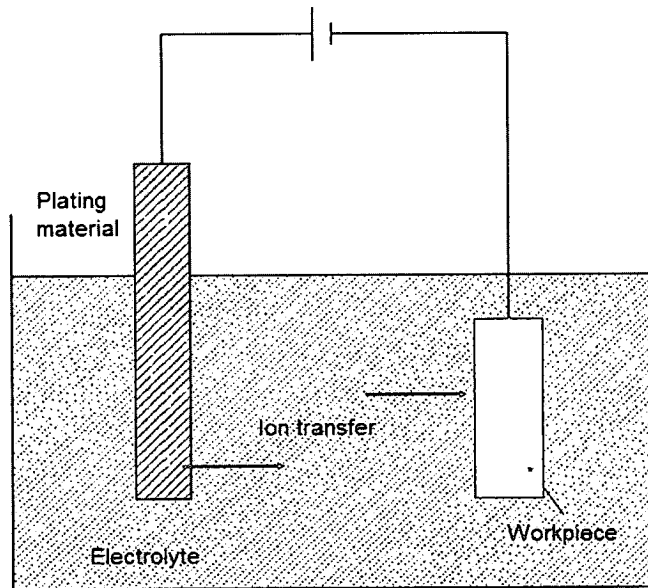


Figure 8: Schematic of the electroplating process

This technique is useful to applying a harder, more corrosion resistant finish to a workpiece whose main body is formed from a softer, potentially cheaper, metallic material. Consequently, this technique is used in the manufacturing of an assortment of products including cutlery and in the chrome plating of automobile parts and hand tools.

2.4 Electrochemical Machining

2.4.1 Overview of the ECM process

ECM is a non-conventional manufacturing process based around the principals of electrolysis. During electrolysis two electrodes, the anode and the cathode, are submerged in a tank containing an electrolyte. A potential is applied between them, an electric field is formed, and current passes between the electrodes through the electrolyte. The application of this electric field causes a migration of ions from the anode to the cathode. This migration not only allows the charge transfer within the electrolyte, but it also results in dissolution of the base metal at the anode (Figure 9). At the same time, hydrogen is released from the electrolyte around the cathode; this is triggered by the large potential gradient between the positively charged ions and the cathode surface causing electrolysis of the electrolyte [31].

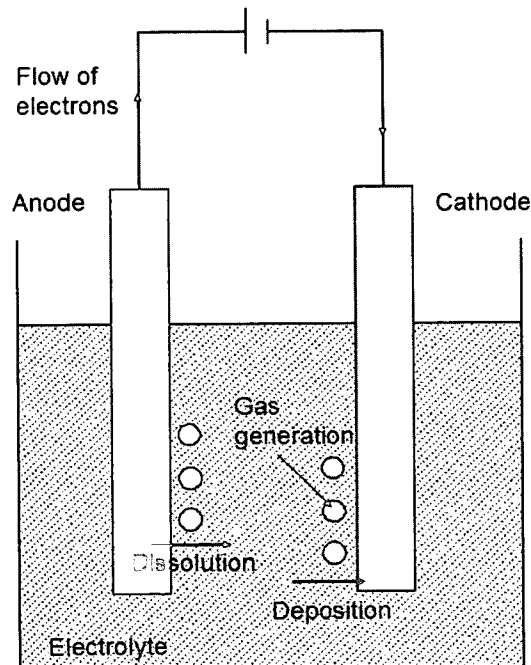


Figure 9: Simple schematic of electrolysis

Faraday's laws of electrolysis state that the rate of dissolution during electrolysis is proportional to the current being passed [31]. Consequently a larger current will

cause more ions to migrate and consequently more material is removed from the anode. It is this dissolution phenomenon that forms the basis of the ECM process.

In ECM the workpiece is set as the anode and the tool as the cathode. Unlike in standard electrolysis, where current values are of the order of a few amps, large current densities are used (up to 5000 A in^2 is reported to be used in industry [2]) to allow a high rate of material removal from the anode. Applying a larger potential between the electrodes and situating the anode and the cathode surface in close proximity achieves these high currents. To maximise the efficiency of the material removal, the electrolyte is pumped between the two electrodes [1, 2]. This removes the gaseous by-products produced at the tool surface as well as the dissolute material away from the machine surface.

During machining either the workpiece anode or the tooling cathode is fed towards the other. This ensures that a high material removal rate is maintained throughout the course of machining. Since the material removal is proportional to the current, the greatest material removal occurs where the current density is at its highest. Over time, as the tool advances, the workpiece will adopt a profile that is an approximate inverse to the tool shape (Chapter 1, Figure 2). This is known as an 'equilibrium' state and the workpiece profile will remain invariant. Since there is no contact between tool and workpiece there is little or no tool wear and no residual stress imparted on the final workpiece.

2.5 Theory of ECM

2.5.1 Die-Sinking ECM using Flat Electrodes

The simplest form of ECM is known as die-sinking ECM. During this process, the tool and the workpiece are orientated in a high-pressure cell with an electrolyte pumped between the two electrodes. A potential is applied and the tool and the workpiece are fed together resulting in material removal at the surface of the workpiece. As the tool moves closer to the workpiece the material removal rate will tend towards a rate that equals the feed rate and an equilibrium condition is reached. To explain some of the theory behind the ECM process, the example of a planar tool machining a flat workpiece will be used. Figure 10 shows a schematic of this simple machining set-up and defines some of the nomenclature that will be used.

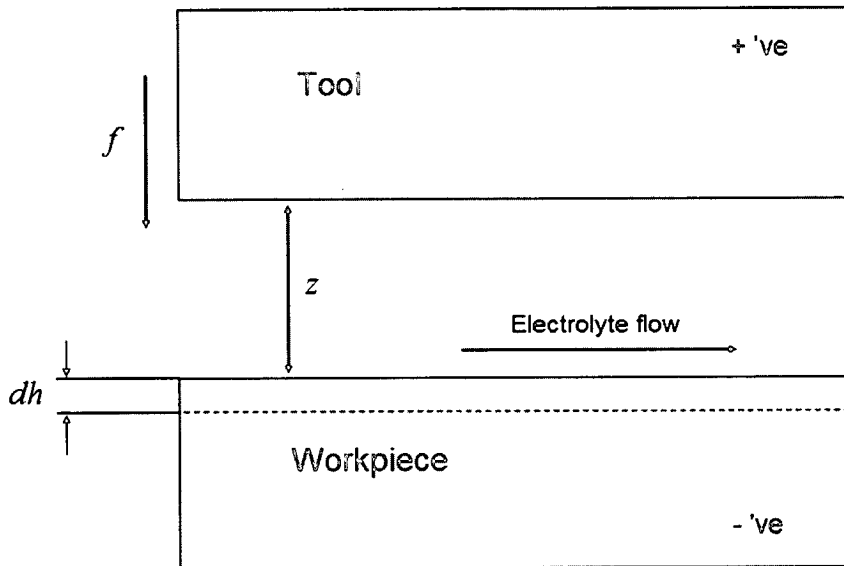


Figure 10: The planer ECM system. In this system f is the feed rate, z is the inter-electrode gap, and dh is the thickness of material removed per unit time from a unit area of the workpiece.

As stated previously the dissolution rate at the workpiece surface is proportional to the current passing. Thus it can be written as

$$m = \frac{It\varepsilon}{F} . \quad \text{Equation 1}$$

where m is the mass of material removed in time t , I is the current, F is Faraday's constant ($= 96,500 \text{ C mol}^{-1}$) and ε is the chemical equivalent ($= \text{atomic mass} / \text{valency}$) and. Consequently the thickness of material (dh) removed from a unit area of the workpiece of density ρ over a time increment (dt) is given as

$$dh = \frac{Jdt\varepsilon}{F\rho} , \quad \text{Equation 2}$$

with the current density (J) defined as

$$J = \frac{(V - V_0) \kappa}{z} , \quad \text{Equation 3}$$

for the case of our flat electrodes where κ is the conductivity of the electrolyte, V is the applied voltage and V_0 is the overpotential. In a more complex example the current density is based on the solution of the Laplace field equation that describes the potential in an electric field, given as:

$$\frac{d^2V}{dx^2} + \frac{d^2V}{dy^2} = 0 . \quad \text{Equation 4}$$

Since the tool surface is being fed towards the workpiece at a rate, f , the total change in gap width, z , over time can be written as

$$\frac{dz}{dt} = \frac{\varepsilon(V - V_0)\kappa}{Fz\rho} - f . \quad \text{Equation 5}$$

By writing

$$C = \frac{\varepsilon(V - V_0)\kappa}{F\rho} , \quad \text{Equation 6}$$

$$\frac{dz}{dt} = \frac{C}{Fz\rho} - f . \quad \text{Equation 5}$$

becomes

$$\frac{dz}{dt} = \frac{C}{z} - f . \quad \text{Equation 7}$$

Once machining at equilibrium the gap remains constant, hence, for the case of our planar electrodes the equilibrium machining gap, z_e , can be calculated as

$$z_e = \frac{C}{f} . \quad \text{Equation 8}$$

Equation 8 indicates that the equilibrium machining gap is primarily dependent upon the conductivity of the electrolyte, the feed rate, the applied voltage and the overpotential. The applied voltage and the feed rate can both be controlled by the ECM operator, however maintaining a constant conductivity, as well control of the overpotential throughout the course of a machining run is impossible. These variations in the parameters controlling the ECM material removal processes are

the principal causes behind the industrial difficulties in predicting a required tool shape to produce the desired final workpiece.

2.5.2 Variations during ECM

In order to understand the variation in the conductivity and the behaviour of the overpotential, this section takes a more detailed look at the processes and the electrochemical behaviour of ECM.

Varying Conductivity

There are two main causes of conductivity variation during ECM; the presence of dissolution by-products in the inter-electrode gap and thermo-electric heating. During electrolysis a series of transport mechanisms and reactions take place. If we use the electrolysis of iron as an example, some of the reactions taking place at the surface of the electrodes can be described as:



In addition to these reactions, there is also electrolysis of water at the anode, releasing oxygen and hydrogen ions into the electrolyte, as well as discharges of anions and cations at the anode and the cathode respectively.

During ECM, continual pumping of the electrolyte between the electrodes serves to remove the gaseous by-products of the electrolytic processes from the machining surface. The rapid removal of these products is important since their presence within the electrolyte alters the conductivity along the inter-electrode gap. Changes in conductivity directly impact upon the efficiency of the machining system. This is especially true when machining at equilibrium, where material removal rates will be at their highest and the machining gap at its narrowest.

Another source of variation of the conductivity is caused by thermo-electric heating of the electrolyte. The currents associated with ECM are high and subsequently the energy imparted in the form of heat into the electrolyte will have a significant effect on the conductivity. As the temperature rises, so does the conductivity.

Varying Overpotential

Overpotential (also known as activation potential) is a term used to describe the potential required to drive the ion movement during electrolysis [31]. If the applied voltage is less than this overpotential then the dissolution and other electrolysis mechanics will not take place. Figure 11 demonstrates that the overpotential, V_o is the sum of the overpotential at the anode (η_w) and the cathode (η_T) during electrolysis.

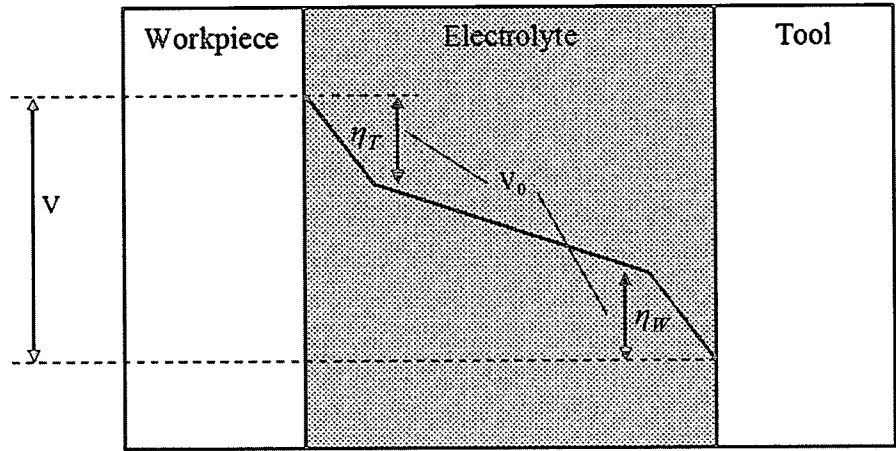


Figure 11: A breakdown of the overpotential during electrolysis

The overpotential at the tool remains constant during machining; hence any variations in the overpotential must be the result of variations in the overpotential at the workpiece. This variation is observed to be linear with current, the result of the ohmic resistance of a passive surface film [32, 33] .

The variation in the overpotential is the focus of a large section of this thesis and is discussed in more detail in Chapters 5 and 6.

2.6 ECM Variants

In addition to the relatively simple die-sinking ECM presented in section 2.5 there are a number of variants of the process that have been developed to maximise the potential of the process. In this section some of these techniques are discussed.

2.6.1 Combined tool machining

This mode of machining is commonly associated with the manufacture of turbine blades. It is similar to the die-sinking approach that was described previously, however, in this method two tooling electrodes are used simultaneously to machine the workpiece from both sides. Figure 12 shows a schematic of such a system.

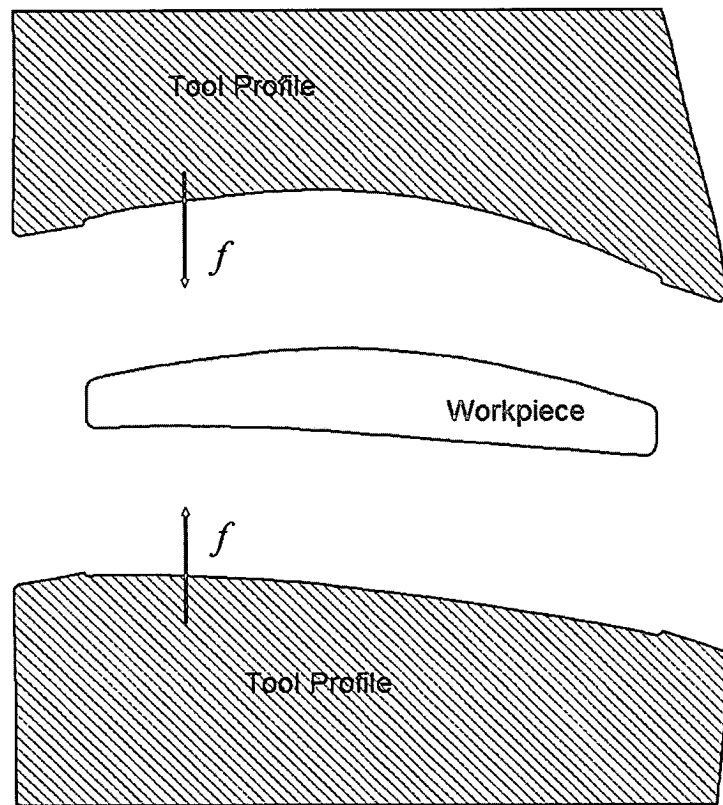


Figure 12: Combined tooling, both sides of the workpiece are machined simultaneously

Due to the nature of this style of machining it is impossible to reach an equilibrium workpiece shape – the leading and trailing edges of the blade will be continually machined. Typically turbine blades need to be manufactured to a high degree of accuracy in order to ensure maximum efficiency, and hence it is of critical importance that the correct machining parameters are established to ensure the correct final shape of the blade is achieved.

The simulation of this type of process is a more complicated problem than that of simulating die-sinking ECM due to the high level of curvatures of the leading and trailing edges. These regions are defined by the complex spatial electrostatic field in this machining area [34]. In addition to this, equilibrium machining will not be reached at the leading and trailing edge of the workpiece - even when the tools are stationary these areas will continually recede. In situations such as this the dominant factors are the initial form of the workpiece, the feed rate and the electrical field.

2.6.2 Ball-ended/universal electrodes

This approach is an adaptation of die-sinking ECM. Instead of using a global tool to form the final workpiece shape, this method takes an approach that is more similar to a Computer Numerical Control (CNC) milling machine. CNC milling involves a single machining head, similar to a drill bit, being moved around a machining area along a predefined path, the kinematics of which are controlled by a computer interface [35]. By removing small quantities of material along this predefined motion path, a part can be fabricated to both a high degree of accuracy. It also removes the need for constant human input into the manufacturing system - bar setting up the code and changing machining heads as required – and also allows manufacturers to mass-produce identical parts quickly at a high level of precision.

The ECM variation of this – machining using a universal electrode [36] – sets the tool electrode as the movable machining head. Again a computer-defined path controls the motion of the tool as it passes over the workpiece (Figure 13). The electrolyte is usually pumped onto the machining area through the tool electrode, ensuring that there is always a suitable conductor to pass the current. One of the disadvantages of pumping the electrolyte in this way is the generation of spikes,

though this can be reduced by adopting an orbital motion [37]. The main disadvantage of this process is the time it takes to machine a workpiece to the required shape [38], however this is offset by the high degree of accuracy (through reduction of heat and gas release during the process [39]) achievable by using this approach. In the majority of cases a ball-ended universal electrode is used, however research has taken place using flat-ended electrodes[†] that offer a higher material removal rate [39].

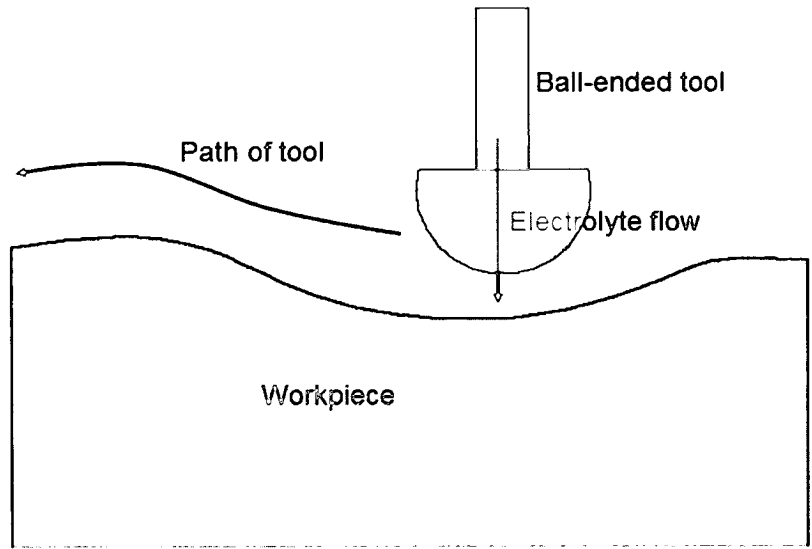


Figure 13: Overview of a ball-ended tool machining a workpiece

2.6.3 Electrochemical Drilling

Electrochemical Drilling uses the ECM process to create drilled features and holes in metallic objects. It is similar to die-sinking ECM, though the electrolyte flows out of the tip of the drill. As the tool moves into the workpiece the electrolyte, and the dissolution debris, is flushed away from the machining area. In order to prevent continuous machining of the sides of the hole, the outer surface of the tool is covered in an insulator ensuring that machining only takes place at the hole base.

[†] The flat-ended electrode must remain perpendicular to the machining surface. This requires the electrode to be controlled in at least 4-5 axes. The ball-ended electrode requires 3 axes.

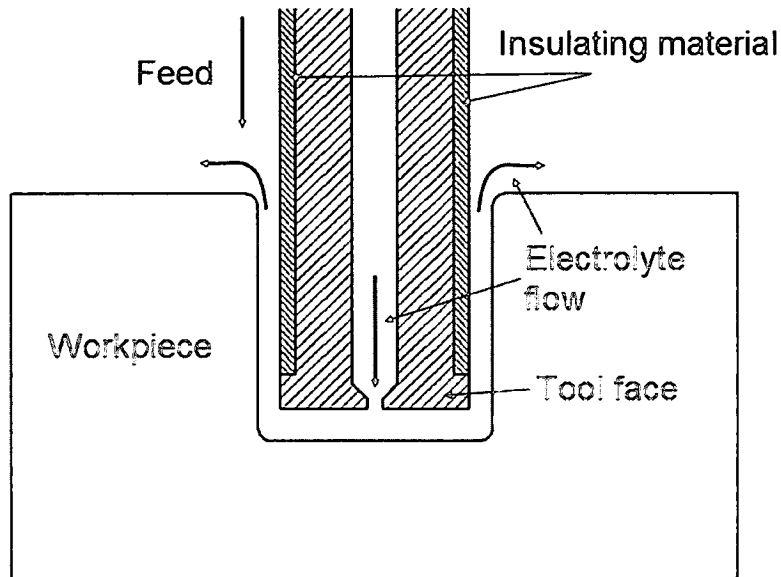


Figure 14: Schematic of the electrochemical drilling technique

Standard, contact drilling techniques are limited by the length of the tool bit allowable. EC Drilling will allow holes that are greater in length and smaller diameter possible through conventional drilling techniques. Though it is effective, it is a delicate and slow process.

Applications of this process include the drilling of cooling holes in turbine blades for compressors [40]. These rely on narrow holes that pass through the blades to aid the cooling during operation.

2.6.4 Sub-sea defect analysis and repair

A problem that is relevant to the oil and other deep-sea industries is the correction of cracks and defects that have formed in lengths of pipe that lie some distance below the surface of the sea. Traditionally in order to replace defects, a section of pipe will be removed followed by a surface based grinding operation to remove the defect, and then replaced. The difficult location and the resulting process ‘down-time’ required means that correcting such defects can prove costly. Additionally the grinding process has been shown to produce residual stresses in the pipe that can ultimately lead to further defects [3]. Consequently a novel system was

proposed by Clifton [3] that uses the principals of electrochemical machining to correct defects in pipes.

The sub-sea ECM system uses a u-shaped, tubular, tool that is formed to match the area of the defect to be removed from the pipe. The tube is slotted to allow the flow of electrolyte to the machining face in the direction of the required cutting path.

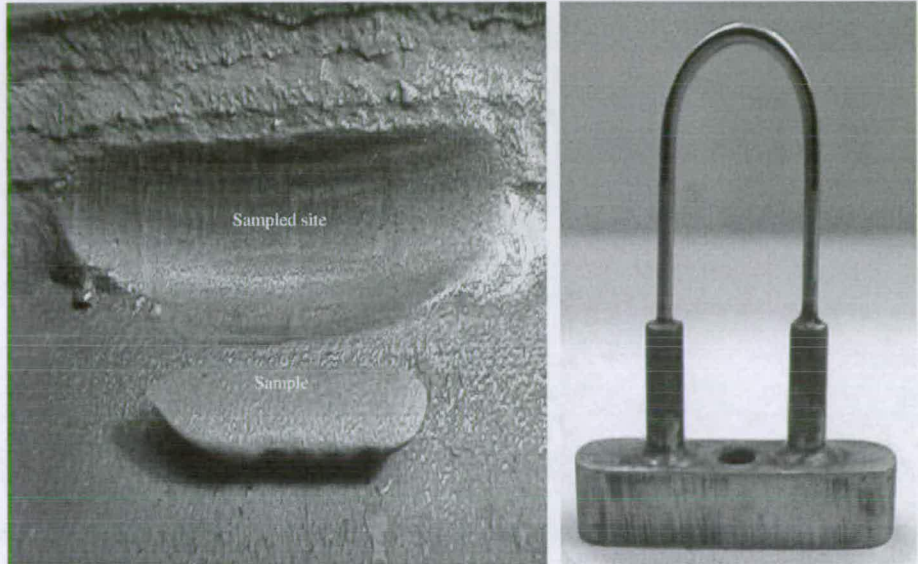


Figure 15: Images taken showing the sample removed from a pipe, and the tool used for the operation (image taken from [3])

As the tool moves along the cutting path the defect is removed in the form of a chip (Figure 15) that can then be retrieved and sent for analysis. Since the ECM process imparts little or no residual stress the clean removal of the defect results in a high structural integrity of the pipe following machining.

2.7 Improving the Industrial Application of the ECM Process

As discussed in Chapter 1, ECM can be a complicated and often expensive manufacturing technique. Two of the key challenges in the manufacturing sector are the design of a suitable tool shape and the calibration of the process parameters themselves. Traditional techniques involve a trial-and-error process of experimenting with different tool shapes and process settings to find an optimal configuration. This approach can often prove to be costly both in terms of time spent as well as financially. In an effort reduce the use of trial-and-error methods and to predict the behaviour of ECM, a great deal of research has taken place into producing simulation techniques of the process. The majority of these are designed either to facilitate the tool design process by offering a tool profile based on the desired workpiece shape or to simulate the machining process to determine a workpiece profile from a given tool. These approaches allow tool design and process set-up to be performed in a virtual, and thus less expensive, environment. The next two sections present some of the different techniques developed.

2.8 Tool Design Methods

The ability to predict the required tool to produce the desired workpiece is a specialised process, requiring an experienced operator to assess the machining conditions and produce a suitable design prior to machining [41]. In order to aid this process and in an effort to remove the need for a specialist operator, different tool design techniques have been presented. The majority of the techniques available are based on methods of predicating the required tool shape to produce the workpiece once equilibrium has been reached.

One of the simplest tool design methods was discussed by DeBarr and Oliver [1] and is known as the 'cos- θ ' method. This approach uses a shape projection based on the angle of the workpiece and the equilibrium gap.

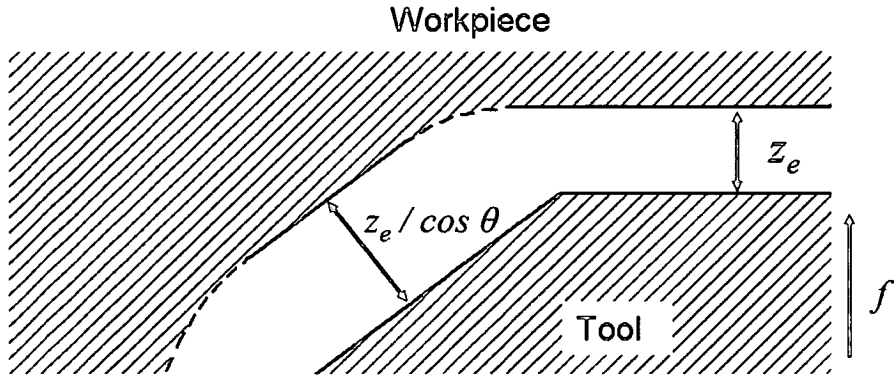


Figure 16: The cos- θ method of tool design (adapted from Oliver [1])

Figure 16 shows a schematic of an arbitrary tool that contains two regions at 0° and at an angle θ to the feed direction. The areas shown in dotted lines are regions of the workpiece that the theory can not be applied to due to the sharp corners on the tool. The cos- θ method can be applied in the solid line regions due to the assumption that the field lines in these areas are straight, parallel and normal to the tool and the workpiece surfaces. A tool surface is predicted by producing a series of normals to the workpiece surface and connecting the resulting end points. This approach is limited heavily by the assumption of straight, parallel and normal field lines. It can not be applied where θ approaches 90° , nor where the curvature of the tool and the workpieces are large compared to the machining gap. This precludes its use for many industrial applications. A complex tool design approach requires solution of the Laplace field equation (Equation 4) that describes the electrical field between the tool and the workpiece.

Since the solution of the Laplace field equation is difficult when using analytical techniques, a number of different variations and extensions of the cos- θ method have been developed. The analogue method [42], is a practical iterative approach - described by Jain, V. K. as “cumbersome” and “approximate” [43] - where a tool and workpiece surface are drawn on a conducting paper and material removal is represented by shifting of the workpiece points until the final shape is invariant. A more analytical approach relies on empirical equations that have been developed to describe the path of the electrical current in the inter-electrode gap at larger θ than accurately dealt with by the cos- θ method [43]. The use of these methods is limited by their applicability to only very specific working conditions only. Furthering this,

a complex variables approach [44, 45] was developed for the cases of shaped workpieces, though are reliant upon simplified assumptions based on experimental findings to facilitate the projection of a tool surface from the desired workpiece. Consequently generalisation is considered difficult due to the ranging complexity of workpieces and the number of parameters that need to be considered during machining.

More complex approaches developed recently have made use of conformal mapping techniques. Alder *et al.* [46], presented work where the workpiece and tool boundaries are represented by a Fourier series. The profiles are mapped to a dimensionless potential-flux co-ordinate system (ψ - ϕ) using conformal transformation (Figure 17). This alternative coordinate system is possible since the lines of flux are normal to the lines of equi-potential.

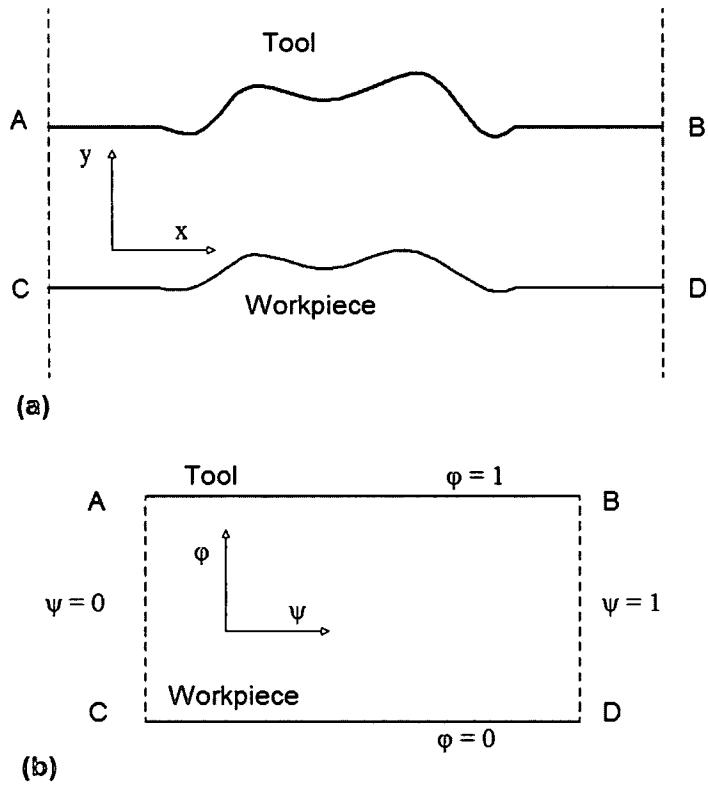


Figure 17: The two co-ordinates systems used by Alder [46]: (a) the physical coordinates; (b) the ψ - ϕ coordinates

The relationship between the two coordinate systems can be written as,

$$Z = Z(W),$$

where Z is an analytical function relating the complex numbers $Z = y + ix$ and $W = \varphi + i\psi$. Of the different Z -functions available Alder proposes the $Z = W + e^W$ is a suitable configuration for the calculation of a workpiece. This approach was validated against experimental data, and a good convergence was found at equilibrium. Though computationally quick, this approach can result in unachievable tool profiles, and a process of filtering may be required to alleviate these issues. Furthering on from Alder's work, McClennan [47] implements B-splines to represent the workpiece and tool profiles. By using B-splines, the harmonic effects present in the Fourier approach are reduced and hence accuracy increases.

An alternative tool design approach involves the use of numerical methods, such as the finite difference, the finite-element or the boundary element methods [48-50] to solve the Laplace field equation. They will often be iterative starting with an initial starting tool profile before refining the geometry based on results of analysis.

Bhattacharyya *et al.* presented a method where an initial tool boundary is formed on the basis of a $\cos-\theta$ projection method [51]. A series of nodes are then distributed along the tool boundary that will allow modifications to the shape to be made. The electric field is solved, and the resulting workpiece shape evaluated. Based on the error between the calculated and desired workpiece shape, the tool points are adjusted accordingly and a subsequent analysis takes place. This process continues until either a set tolerance has been reached or a maximum number of iterations has been exceeded. The success of this method is dependent upon the input geometry, the complexity of the geometry and also the method used to evaluate the point adjustment.

Jain *et al.* presented a number of papers on the use of FEA in the simplification of the tool design process in ECM. Early work involved the modification of the $\cos-\theta$ method through FEA calculation of temperature variation within the inter-electrode gap [52]. This was then extended to produce an iterative FEA system that solved

the Laplace equation and introduced a tool correction method [53] based on an analysis of the deviation between a workpiece given by the current tool profile and the desired workpiece profile. If the error is too great, the tool profile is adjusted and the algorithm loops again. This work led to the proposal of an integrated tool design system, where experimentally collected process information, and FEA tool design methods are combined to speed up and reduce the cost of, tool design [54].

Up to this point the majority of the methods presented here make the assumption of an ideal system. Other approaches have made attempts to incorporate some of the variable parameters that occur during machining. Chang *et al.* investigated the effect of thermal-fluid properties in determining the tool shape using a finite element method [55, 56]. Starting with an idealised system, this work incorporated additional functions to describe the effect of electrolyte heating and the development of a void fraction into the tool design process. Again an iterative procedure was used to modify the tool surface based on the error between the workpiece produced by the current tool and the desired workpiece shape.

Though the complexity of these tool design techniques has increased, they still share the same trait: the given tool shapes are reliant upon equilibrium having been reached. In a number of different engineering applications the assumption of equilibrium can not be made, and consequently a different approach is required. With this, and the desire to monitor and predict more of the process parameters of an ECM system, methods of simulating the machining process have been devised.

2.9 Simulation of the ECM process

The techniques for simulating the ECM process can, broadly speaking, be split into two categories: those that are based on analytical techniques and those that utilise numerical techniques.

2.9.1 Analytical Techniques

An early analytical attempt [57] to simulate the resulting workpiece from a given tool shape at equilibrium was based on the same theory as the $\cos-\theta$ method of tool design (discussed above in Section 2.8). Since the $\cos-\theta$ method is performed using the angle of the workpiece normal to that of the tool, an adjusted method is required to produce the workpiece profile from a known tool-profile. This involves a projection of the tool surface, based on the local tool surface normals. At points along this initial projection, the profile is adjusted via a series of geometric operations calculated on the difference between the tool normal and the first approximation normals. In this manner, the first approximation boundary is shifted to produce a new profile, considered to be the machined surface of the workpiece at equilibrium.

More advanced methods were presented by Kozak [58] who presented a series of mathematical models to account for the deviations in the workpiece surface arising from the variability of machining conditions. Included were models for the flow, pressure and temperature variations in the electrolyte, as well as the concentration and current density distribution on the surface of the electrodes, their polarisation and the efficiency of dissolution. This work also made use of the assumptions seen in the $\cos-\theta$ method, namely that the curvature of tool and workpiece is small compared to the size of the gap. Subsequently, these mathematical models were used in a paper discussing tool design through use of iterative, numerical methods [59].

More recently, with the limitations in solving the Laplace equation effectively using analytical techniques, methods have been devised specifically to suit applications of ECM where the approximations of straight field lines, approximately normal to tool and workpiece are made. Hocheng [60] discusses the

mathematical models behind the simulation of ECM using universal electrodes. In particular it focuses upon machining using a flat, rectangular electrode rather than the more popular ball ended electrodes. The mathematical derivations presented offer a model that is similar to the die sinking method of material removal, though the gap is approximated to be a constant value.

A more advanced analytical technique was presented by Zhitnikov [61] who makes use of conformal mapping techniques, similar to those applied to tool design (Section 2.8), to represent the curvature of the workpiece in the form of a more usual geometric object for example a circle. This work demonstrates the evolution of a workpiece boundary over time, using both a stationary and a non-stationary tool.

2.9.2 Numerical Techniques

Numerical simulation techniques such as the finite difference method, the finite-element method and the boundary-element method have increased in popularity with the development and rising accessibility of computing power. In terms of ECM, numerical methods are used to solve the Laplace equation, and model variable process conditions.

An early technique presented by Konig [62], used an iterative finite-difference approach to approximate a solution to the Laplace equation in the inter-electrode gap. The work aimed to parameterise the inter-electrode gap whilst machining through a method of process characterisation to determine the effective material removal. Using this data, an iterative process was established that used a simple, finite difference solution to calculate the field intensity at the workpiece. This work corresponded well with experimental results, though the solution to the Laplace field equation was simplified and the geometries presented were relatively simple (smooth, long, curved surfaces).

The finite-element method (FEM) relies on the discretising of a subdomain – in the case of ECM it is the inter-electrode gap – into individual elements. The solution to the Laplace equation is determined by an iterative process where a series of linear equations are formed and solved based on initial boundary conditions at each of the

nodes. In this manner an approximation of the electrical field can be determined. Since the subdomain is entirely discretised then additional solutions for heat transfer and flow fields can be incorporated into the solution. The addition of non-ideal elements is discussed in Section 2.9.3.

Hardisty *et al.* have presented a series of work investigating the applicability of the FEM to the simulation of the ideal ECM process. The work presented demonstrates the method for the machining a flat workpiece surface using a stepped tool [63, 64] producing good correlation with experimental results. This technique was then developed to represent the more complex system of machining using a parabolically shaped tool machining and an arbitrarily shaped surface [65]. They also invert the process, and suggest a methodology of using the FEM approach to producing tool designs from a given workpiece. Though results are promising, the technique used requires the manual adjustment of the coordinates of one of the side boundaries of the system to account for the condition of the electric field at the electrolyte entry point.

The use of the boundary-element method (BEM) is preferred by some as, the boundary alone needs to be discretised into segments, thus reducing the dimension of the solution by an order of magnitude. Though this reduces computation time, the limitation is that the BEM will assume the domain to have homogenous properties.

Narayanan *et al.* [66] presented the use of the BEM to simulating ECM through the simulation of rectangular and rounded tools. The effect of using linear and quadratic elements, the number of node points used to describe the workpiece surface, and the magnitude of the time-step were all evaluated. From the results presented, it is clear that the use of quadratic elements and more nodes produced the smallest deviation from experimentally derived results during equilibrium machining. Deconnick [67] also demonstrates the technique with the use of a Newton-Raphson method to produce a more rapid convergence than when using a successive approximation method to solve the system of equations.

2.9.3 ECM Simulation under Non-ideal Conditions

In general, the work presented in the previous sections share a common theme in that they assume constant, idealised, conditions during the simulation time. In practise the ECM process is more complicated with different interactions causing changes in parameters that govern the system [68]. Consequently attempts to introduce the variability of some of the machining processes taking place within the inter-electrode gap have taken place.

Jain [69] presented a finite-element technique based on simple triangular elements for both planar and more complex tool surfaces as a more accurate alternative to the finite-difference approaches available. The finite-element analysis used here relied on simple triangular elements that use linear interpolation between node points. The method is not iterative and the solution of this FE mesh results in a given workpiece profile at a time inputted by the user. However, this approach does take into account the effects of temperature and void fraction in the electrolyte as a function of the flow path.

Nied, H *et al.* [70] further this work by incorporating the temperature and void fractions into an interactive simulation where the workpiece boundary varies as a function of time. This work also recognised the need to include more accurate models for the chemical behaviour at the anode, and in particular highlights the overpotential as an important parameter. Consequently it incorporates a model where the overpotential is described as a function of electrolyte temperature.

More recently, Filatov [71] presents a more detailed evaluation of the two-phase flow taking place in the inter-electrode gap. This work describes the two-dimensional simulation of the ECM process with a particular focus upon the simulation of the fluid and gas mixture found in the inter-electrode gap during die-sinking ECM. It defines a series of equations that define the conductivity of the electrolyte in terms of properties of the two-phase fluid flow e.g. pressure, temperature, relative concentrations of gas and liquid. These equations are solved using the finite-difference method and it presents results describing the effect of a number of behavioural characteristics of the electrolyte during steady-state

machining including velocity, pressure and temperature distributions, on the material removal rates at the anode surface.

2.9.4 Simulation of ECM variants

As discussed in Section 2.6, there are a number of variants to the standard die-sinking ECM method. As a result, a number of papers have been published concerning the simulation of such methods.

Kozak *et al.*, have presented a large body of work concerning the simulation of ECM when using ball-ended and universal electrodes. Simulation results have been presented for machining when using a universal electrode that moves on a complex path around a non-flat starting workpiece [72], as well as ball-ended electrodes [73]. In other work, Other variations such as EC-drilling [74], deburring [75], micro-machining [76] and the modelling of multi-stage ECM [77] (where more than one variant is used) have also been reported upon.

Further developments in the numerical simulation of the ECM process have led to the development of three-dimensional simulation tools. Kozak presents a number of mathematical models describing non-ideal conditions for 3-D ECM simulation, using the CNC-style variant as the basis of the work [78]. Purcar *et al.* [79] presents a time-dependent numerical method that uses BEM to solve the potential model. The technique presented adjusts the node points of the workpiece boundary mesh to simulate machining, though this surface is not then re-meshed as the shape evolves, potentially leading to problems if the workpiece shape changes dramatically, or greatly recedes from the starting shape. Results are presented for the simulation of machining of a letter 'E'. These results represent 34 minutes of actual machining though it simulates using only 10 time-steps i.e. each time-step is representative of 3 minutes 25 seconds. The simulation results showed the evolution of the workpiece, though this work was not verified against actual experimental results. Volgin *et al.* discuss the use of the FEM to simulate the evolution of complex workpiece surfaces [80], citing the limitations of the one-dimensional models that rely on the assumptions seen in the $\cos\theta$ method. The method uses finite volumes to describe the inter-electrode gap, and results are

presented showing the evolution of a workpiece with a complicated form. As is often seen though, this work does not produce validated results.

2.9.5 ECM Simulation Software

With the body of research on the simulation of the ECM process growing in size, there is a demand for simulation software that allows the user to produce their own workpiece and tool shapes for simulation. In 2000, Domanowski and Kozak introduced software that enabled the machining parameters to be defined for electrochemical generating machining in two-dimensions [39]. The initial and required final workpiece shapes are defined and the software then calculates the required trajectory of the tooling surface to create the transition between the two. Following on from this Kozak *et al.* [81] subsequently presented the concept and a prototype of a CAE-ECM system that was capable of simulating a number of ECM variants and monitoring machining variables over time. The prototype was then developed further in a subsequent paper [82], where details and results of simulation using ball ended electrodes are presented.

One of the more advanced systems currently being developed has been presented by Bortels *et al.* [83]. They present a “user-friendly” software tool that integrates with a mainstream CAD package for 3-D ECM simulation. The solution to the Laplace field equation is based on the BEM, whilst it also incorporates FEM to model internal potential variations in the electrodes. Geometry is meshed and boundary conditions applied through a graphical user interface.

2.10 Conclusion

ECM is a useful, but complex machining technique. The demand to manufacture parts from hard materials is such that the ECM process has the opportunity to thrive. This, however, is dependent upon reducing the uncertainty that arises from the inter-dependence of process parameters and the reduction of trial-and-error methods for process set-up and tool design. To encourage the successful and widespread, application of the ECM process, tool design methods and simulation techniques to advance the industrial applications of ECM are of great importance. These methods are entirely dependent upon the formation of an extensive knowledge base through characterisation of the process.

With this in mind, the remainder of this thesis presents research undertaken to produce a time-dependent simulation of the ECM process. The industrial applicability of the simulation will be demonstrated followed by the introduction, based on experimental characterisation results using a unique ultrasound measurement system, developed by Clifton et al [87, 88], of a parameterised overpotential model into the work.

Chapter:

3 Developing a Time-Dependent Simulation

This chapter outlines the background work and development of the time-dependent ECM simulation. Detailed are the algorithms used and the rational behind the decisions made in the creation of this simulation tool. Finally results are presented for the simulated machining of a complex tool shape.

3.1 Introduction

This chapter presents the details of a time-dependent simulation of the ECM process developed during this research. Outlined are the algorithms that form the basis of the simulation as well as explanation for the methodology used. The work relies on moving boundary FEA techniques to produce a time-dependent simulation of the ECM process.

This work uses two widely available commercial packages, MATLAB and FEMLAB 3.0, to construct the simulation. MATLAB (developed by The Mathworks, Inc.) is a high-level language and interactive environment that specialises in performing computationally intensive tasks faster than using alternative programming languages. Large quantities of data can be manipulated quickly through a range of data analysis and visualisation options. FEMLAB 3.0 is a FEA package produced by Comsol Inc. It is described as a “multi-physics modelling package” that is capable of solving a variety of scientific and engineering problems. It offers a range of predefined solver as well as offering the ability for the user to define customised models based on partial differential equations. FEMLAB integrates with MATLAB and allows the user to define models both within the GUI and also from the command line.

3.2 Commercial Packages vs. Self-Programmed

For this work the author elected to make use of a commercially available FEA package, FEMLAB, to perform the FEA solution of the Laplace field equation. The alternative approach was to develop an original code that would mesh and solve the required geometries. The decision was taken to use the FEMLAB software for the following reasons:

Ease of implementation

The author had very limited coding experience prior to starting the research and it was decided that to take advantage of the commercial FEA tools, such as the adaptive meshing and solver in FEMLAB, would reduce the learning curve required to produce meaningful results in the allotted time frame.

Integration with existing CAD packages

One of the fundamental aspects of this project was to create a simulation that could be used as a meaningful tool in an industrial environment – in particular that of Dutch Aero (formally Philips Aerospace). The FEMLAB software allows for easy importing and interpretation of CAD geometries, making it an attractive option for this work.

MATLAB integration

The FEMLAB software allows the user to access and run a number of the key solver commands from the MATLAB command line. This meant that the ECM calculations could be directly integrated with the solver commands to produce a streamlined, time-dependent simulation.

3.3 Moving boundary FEA

The time-dependent nature of the required simulation means that an iterative, moving boundary solution was required. This requires the implementation of moving boundary techniques and multiple FEA solver iterations. At the time of writing the FEMLAB software is incapable of automating such complex moving boundary problems effectively and hence the tasks required to implement such an algorithm have been implemented by the author using external MATLAB scripting techniques. The result is a simulation that can be considered in two sections: the FEMLAB FEA solver (handling the meshing of geometries and solution of the Laplace equation) and the ECM code in MATLAB (converting results from the solver into material removal and geometry manipulation). For the purposes of this discussion, the development work has been split into three areas: the pre-processing requirements, the processing requirements and the post-processing requirements.

3.4 Pre-processing Requirements

The first stage of the simulation is to define the key parameters and geometry of the desired machining run. It is in this section that the operator of the simulation has the most input.

3.4.1 Defining Input Parameters

Upon running the simulation the user will be asked to define a number of important parameters that will be used in the ECM calculations. The simulation has been designed so that the required inputs are based around settings that would be used in the actual machining process. The user is also required to input some parameters that help control the manner in which the simulation runs. Since this simulation was primarily designed with the experimental set-up used by the ECM group at The University of Edinburgh, a number of the settings required the input in non-conventional units. These were automatically converted to SI units within the code. Where such cases exist the units required for the inputs are indicated below.

Process Parameters

Workpiece material. Initial simulations required that material properties of the workpiece material were defined individually at the start of the simulation. This was later replaced by a method that used an internal store of the material properties and the user simply selected the required material from a list. The properties required are the density, the atomic mass, valency, and overpotential.

Feed rate (mm/min). The rate at which the tool will approach the workpiece during the simulation.

Starting Gap (mm). This defines the distance that the tooling geometry is located away from the workpiece at the start of the simulation. The distance is applied from the point of the tool profile that will be nearest to the workpiece profile.

Conductivity of electrolyte. This value was applied to the subdomain in the FE analysis.

Applied machining voltage. This, in conjunction with the overpotential, was used to define the boundary conditions for the tool and workpiece profiles in the FE analysis.

Simulation Parameters

Time-step required (s). This parameter defined the length of each iteration during the simulation. The choice of length of time-step is important to ensure satisfactory results. Using a large time-step results in less iterations and subsequently less processing is required. However, if the time-step is too large the simulation may fail as the moving boundaries may overlap. Equally the material removal may become too large and subtle geometric changes are obliterated. If the time-step is made excessively small then a large number of iterations are required and the amount of data generated may become prohibitively large.

Total simulation time. The length of the total simulation. This exit condition was useful if machining to non-equilibrium states or whilst validating experimental results.

Tolerance level for running to equilibrium current (An alternative exit condition). This method worked on the principal that the simulation would be allowed to run until the current being calculated reached a steady level – implying equilibrium machining was taking place. The user could define a tolerance, in Amps, that would be used to assess the “steadiness” of the current during the simulation. If the current did not change by this value for a number of consecutive time-steps then the simulation was assumed to have reached its required end point.

Video recording option (y/n). A useful tool for the presentation of simulation results. As the simulation progresses a window shows the current geometric arrangement to the user. By selection yes to the video record option, an .avi file showing the evolution of the machined workpiece is automatically compiled.

3.4.2 Defining Geometry

The geometry used in this simulation describes the shape of the inter-electrode gap i.e. the electrolyte region. Consequently the shape of both the tool and the workpiece form the upper and lower boundaries. These two profiles are connected via straight sides at either end (See Figure 18 and Figure 19).

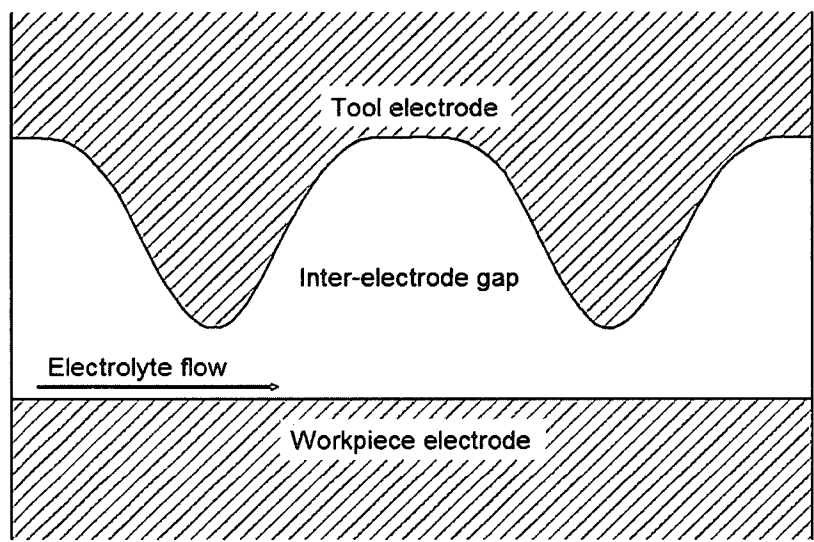


Figure 18: Schematic of a sample tool and workpiece geometry

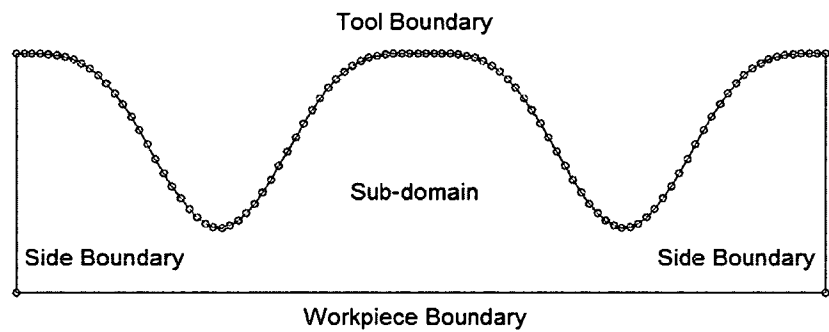


Figure 19: Corresponding ECM simulation geometry

There are a number of ways the user can define the geometry in the ECM simulation. The required profiles can be created by importing a CAD file created in a separate package into FEMLAB; draw a geometry using the available FEMLAB

design tools; or define using Cartesian point data, the profile in an input script file. Once the required starting geometry has been defined or imported, no further input is required from the user – the conversion from the basic FEMLAB geometry into a model suitable for ECM simulation takes place automatically.

3.4.3 Creating a movable boundary

Since the workpiece boundary will define the profile of the machined surface, it needs to be able to represent the varying curvatures at a suitable resolution. In order for this to happen the user is asked to define the number of points (N) that are required to represent the workpiece surface. These N points need to be distributed evenly along the workpiece profile to ensure that material removal takes place evenly during the simulation. Once the points are distributed new boundary geometries need to be fitted between each of the N points to close the subdomain. The simplest approach is to assume that a flat workpiece boundary is used in the starting geometry. In this scenario the N points can be distributed linearly in a straight-line between the x_{min} and x_{max} values of the starting geometry with $y_i = T_{ymin} - z_0$, where T_{ymin} is the lowest point on the tool boundary and z_0 is the starting gap required (Figure 20).

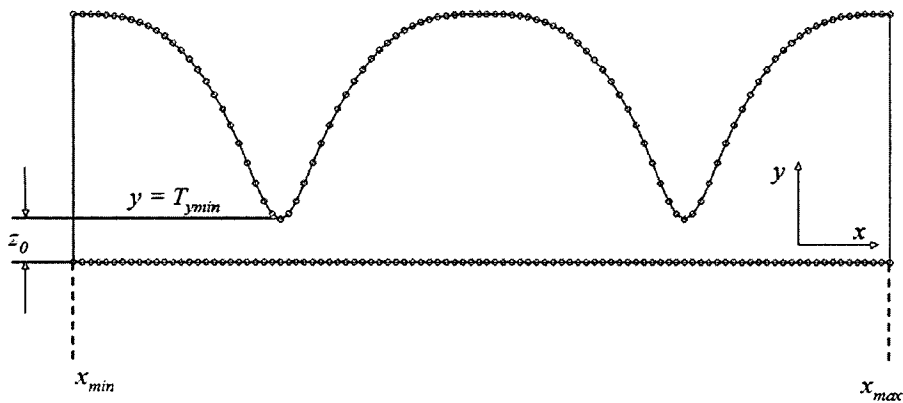


Figure 20: Distribution of 100 starting points along the workpiece boundary

This is a limited solution and one that fails when the starting geometry does not use a flat workpiece boundary¹. In addition, this point distribution process is also required when material removal is taking place i.e. the workpiece is no longer flat, meaning a more robust method at this stage is required.

The first task in achieving this is to identify the location of the existing boundary objects in the starting geometry. The methodology for this process exploits a labelling system that is used by FEMLAB. Each boundary section (Γ_j) within a FEMLAB geometry is assigned a unique ID number (j) that is used when applying boundary conditions. The labelling system adopts a ‘ $-x$ to $+x$ ’ ordering system, where the boundary beginning at x_{min} is assigned an ID value of $j = 1$. The next boundary segment along the x -axis to have a start point is assigned $j = 2$, the next $j = 3$, *ad continuum*. In the event that two boundaries start at the same x -location – the x_{min} of the tool and workpiece boundaries are such a case – FEMLAB evaluates the start points of Γ_j based on a secondary ‘ $-y$ to $+y$ ’ system before assigning the boundary ID number.

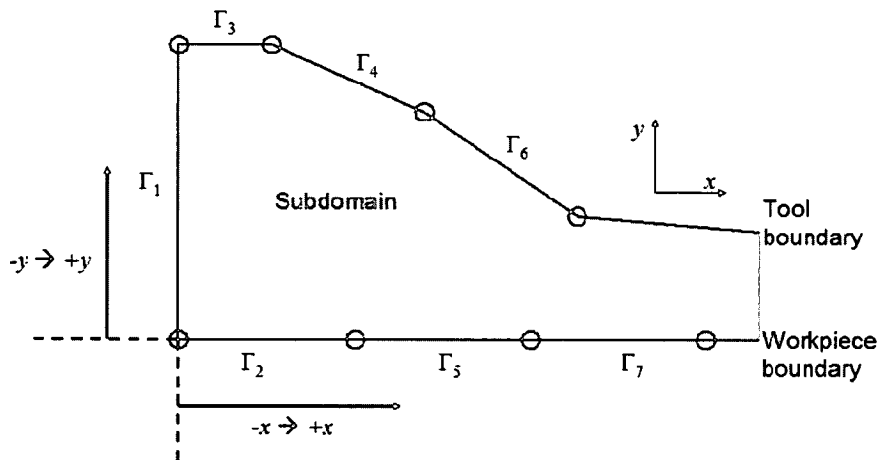


Figure 21: A generic example demonstrating the boundary ID numbering system in FEMLAB

¹ See Chapter 4 for a discussion on the implementation of a non-flat starting workpiece

Since the ECM simulation will always have a boundary connecting the x_{min} coordinates of tool and the workpiece, the Γ_1 will always be the side boundary. Similarly the first workpiece boundary will always be assigned Γ_2 and the first tool boundary will be Γ_3 . This information is vital for determining which other boundaries form both the workpiece and the tool.

Starting with the knowledge that Γ_2 is the first of the workpiece boundaries; the ECM script then extracts the connectivity data that is stored in the FEMLAB geometry. This connectivity data is in the form of a matrix that stores pairs of boundary ID numbers that are connected to each other. Through use of a searching and storing algorithm, the ECM code locates the boundary that is connected to the initial input boundary, Γ_2 . This new ID is then added to a central index, and a new search is initialised using this new value as the search term. By iterating through this searching and storing algorithm, an index of all the Γ_j that define the starting workpiece boundary is formed.

Since the geometry is composed of a continuous loop of M -boundary segments, the algorithm again exploits the boundary labelling system to ensure only the boundaries that describe the workpiece are stored - this time through the knowledge that the side boundary furthest along the x -axis will have an ID equal to the total number of boundaries in our starting geometry (Γ_M). Once the workpiece identification algorithm has found a boundary that is connected to this maximum ID number it will stop searching. Figure 22 shows a flow chart of this process. An identical process is used to identify the tool boundary sections.

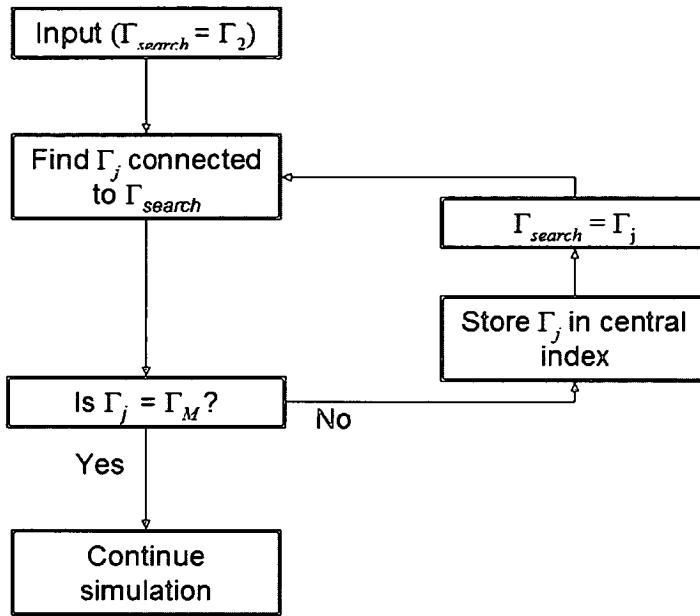


Figure 22: Flowchart describing the algorithm for determining connectivity between boundary sections

3.4.4 Defining FEA conditions

The final task before the simulation is initialised is to apply the necessary boundary and subdomain conditions to the geometry. The user has defined the values for these boundary conditions previously. The user-defined applied voltage (V_t) and the overpotential (V_0) are assigned to the workpiece boundary. The side boundaries are constrained to ensure that the normal of the current density (nJ) is equal to zero. In the subdomain the conductivity is set to the user input of κ .

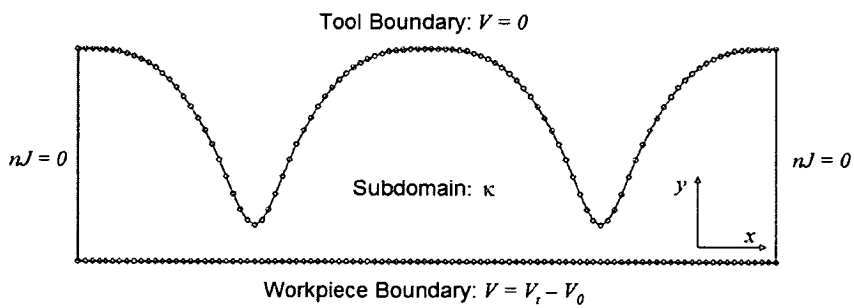


Figure 23: The boundary and subdomain conditions used in the ECM simulation

3.4.5 Additional set-up processes

In addition to the steps shown above there are internal set-up routines that take place to aid the processor section of the simulation. These are:

- Establishing empty arrays to store data generated by the simulation for post-processing purposes.
- Calculation of the chemical equivalent (ε),

$$\varepsilon = \frac{A_M}{n} ,$$

where A_M is the atomic mass and n is the valency of the workpiece material.

- Conversion of feed rate from mm/min to the SI units of m/s.

3.4.6 Defining the FEMLAB Data Structure

Whilst the simulation is running, data is being systematically transferred between FEMLAB and the ECM code. Some of the data being generated and manipulated – such as the location of the workpiece coordinates – does not need to be transferred into FEMLAB and can be stored solely within the ECM code. Other data, however, needs to be passed between the two environments. To accomplish this, a data structure is generated that can be interpreted, manipulated and passed back by FEMLAB.

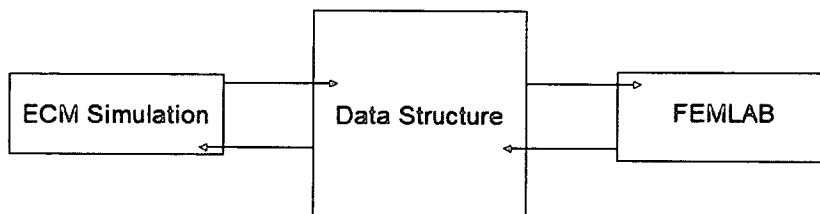


Figure 24: The data structure allows information to be passed between the simulation code and the FEMLAB software

During the pre-processing stage, this data structure is generated and contains a variety of information including the inputted geometry and the required boundary and subdomain conditions, defined by the user. Table 5 shows a breakdown of all the information contained in the data structure passed initially from the ECM simulation to FEMLAB.

Table 5: Overview of the data structure passed into FEMLAB following the pre-processing stage of the ECM code

Field	Sub-Field	Information
<i>Geometry</i>	n/a	Contains the defined geometry profile
<i>Constants</i>	n/a	User-defined constant values: V_b , V_0 , σ
<i>Application information</i>	Mode	Describes the FEMLAB mode the solution will take. For the ECM simulation this is defined as ‘Conductive Media - Direct Current’.
	Boundary	Defines the different boundary condition types required (voltage, ground, normal current density) as well as the values to be assigned (identical to constants field). It also contains the boundary index and which condition and value is to be assigned.
	Subdomain	Defines the subdomain type, the conductivity, and the subdomain ID.

3.4.7 FE Analysis

FEMLAB interprets the geometry structure and applies the required boundary and subdomain conditions. The software then initialises a mesh within the subdomain. The mesh used is a triangulated, quadratic mesh constructed out of Lagrangian elements. Meshing with the FEMLAB software is adaptive meaning that in areas of high curvature a finer mesh is used to define boundaries. Since the ECM simulation will be expected to remain accurate even when the subdomain width is narrow i.e.

small inter-electrode gaps, the ECM code instructs the FEMLAB software to refine the mesh once. This increases the number of mesh elements within the subdomain.

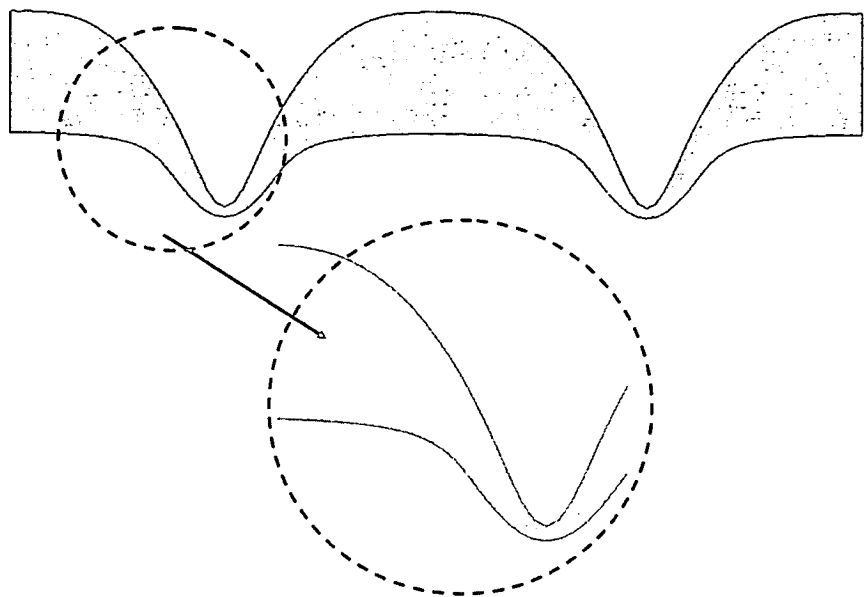


Figure 25: Meshed subdomain including detail section taken from a geometry midway through an ECM simulation. This typical mesh consists of 5,000 elements

The calculation of the electric-field within the subdomain is based on the solution of the Laplace field equation:

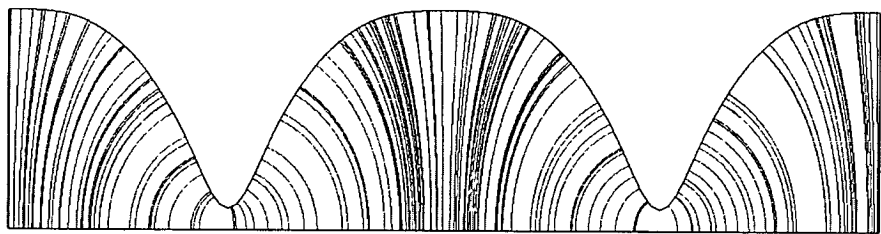


Figure 26: Diagram showing the calculated electric field using a stream-lined representation

Once completed both the mesh and this solution is then stored in the data structure. This updated data structure is then passed back to the ECM code environment and the calculations for the simulation of the process can be made based on the FEA results. Table 6 shows the additional fields that are added to the data structure.

Table 6: The additional fields added to the data structure by FEMLAB		
Field	Sub-Field	Information
<i>Mesh</i>	n/a	Details of the mesh including node points, mesh type, degrees of freedom
<i>Solution</i>	n/a	Contains the solution values at each of the node points of the mesh

3.5 Processing Requirements

Once the pre-processing section of the simulation has been completed the algorithms required to produce the simulation of ECM are brought into effect. One of the key aspects of this simulation of the ECM process is that it is time-dependent. As machining progresses the workpiece boundary used in the simulation will need to adapt in response to the material removal. To achieve this, a moving boundary FEA system needs to be established. The overall process can be described by the flowchart shown in Figure 27.

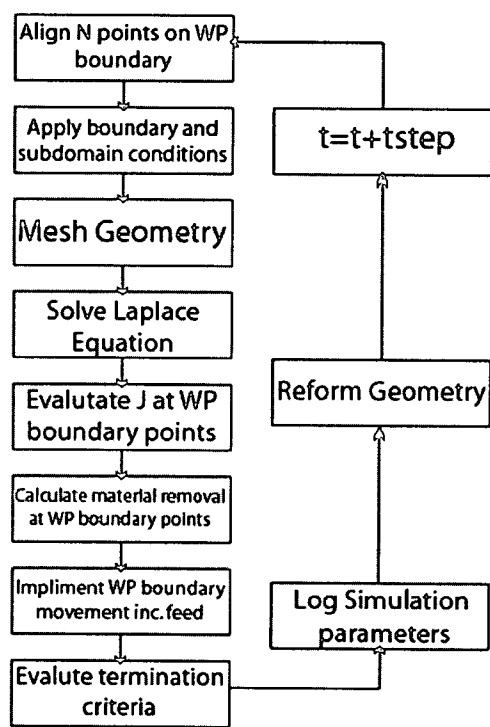


Figure 27: Flowchart of the processor algorithm ('WP' = workpiece)

3.5.1 Data extraction

Once the solution to the Laplace equation has been calculated and stored in the FEMLAB structure it is necessary to extract the relevant data needed to perform the material removal calculations. Since the material removal is based on the

current density at the workpiece (Chapter 2) it is this information that needs to be extracted from the solver section of the FEMLAB data structure.

In terms of FEA this equates to extracting the current density along the workpiece boundary of the geometry. This requires a selective extraction, since the current density at the tool boundary or on the side boundaries is not required. To ensure the ECM code only extracts the data from the workpiece boundary elements the simulation calls the workpiece boundary index that was created in the pre-processing stage. Using automated FEMLAB commands, the current density (J) at the mesh node coordinates that lie on the workpiece boundary can be retrieved and made accessible for manipulation (Figure 28).

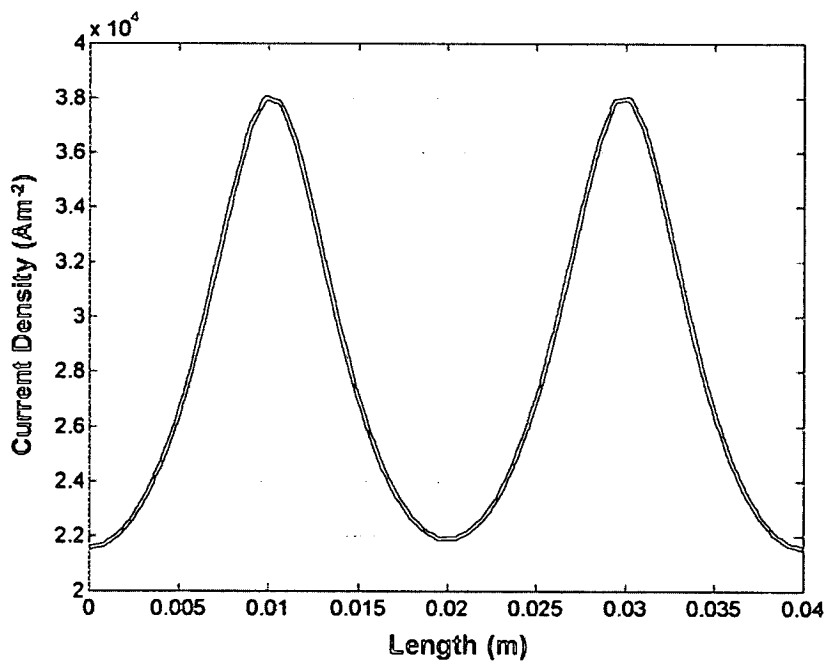


Figure 28: Sample graph showing the spline function of the current density along the workpiece

This output is in the form of a spline based on the arc length of the workpiece.

3.5.2 Calculating material removal

Material removal at a boundary point during ECM simulation is defined by the following equation:

$$\frac{\overrightarrow{dh}}{dt} = \frac{Jtn}{FM\rho} \cdot \text{Equation 9}$$

The N points distributed along the length define the workpiece boundary; hence the algorithm needs to use the extracted data to find the corresponding N current density values for each of these workpiece points.

Since the nJ boundary function is in the form of a spline, in order to extract data from it the Cartesian coordinate workpiece coordinate format needs to be converted into a form that allows the arc length between them to be calculated. By calculating the absolute straight-line distance between each of the N points and combining these values, the total arc length of the workpiece can be determined. This data can then be used in the formulation of a spline generated to fit through these points. Using this spline and the original workpiece coordinates it is possible to extract the distance by arc length along the workpiece boundary that each of the workpiece coordinates lie. The corresponding J values are then evaluated for each of the workpiece coordinates and the corresponding dh is calculated.

3.5.3 Movement of workpiece boundary

Since material removal takes place in the direction of the local normal of the workpiece surface it is necessary to also collect the surface normal at each point along the workpiece boundary. The spline created previously is differentiated to give the gradient of the workpiece boundary. The inverse of this gradient is then taken at each workpiece point to give the normal to the boundary and the new locations of the workpiece coordinates are calculated.

One of the key issues with this, and other moving boundary problems is the prevention of unphysical geometries being generated when shifting boundaries.

Essentially this can be interpreted as the prevention of adjacent points ‘crossing over’ one another when they are re-located. This is illustrated in Figure 29.

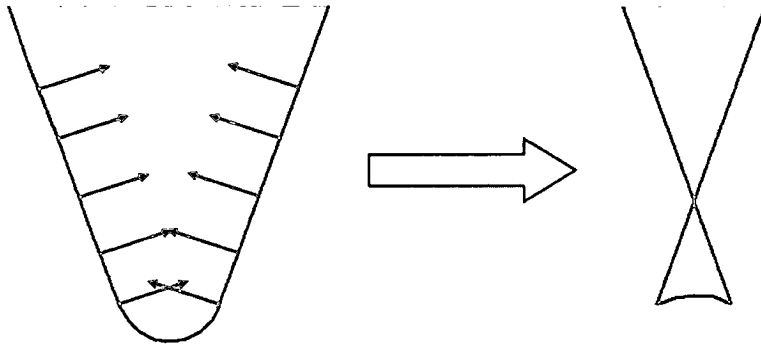


Figure 29: Diagram demonstrating how the effect of point cross-over can result in unphysical geometries

One way of preventing this is for the user to use a small time-step resulting in less material removal during each iteration. This has two drawbacks, the first being that a smaller time-step will result in an increased total time for simulation, the second is that there is no guarantee that this smaller time-step will not still produce geometric cross-over. A more robust and automated way of implementing such a safety net is to assign a maximum translation distance based on other simulation parameters. Since the points are originally equally spaced along the arc length a good assumption is to set the maximum point-shift that can occur as half this distance.

Another restriction that needs to be made is to prevent the end points of the workpiece boundary moving in the x -direction. This ensures that the integrity of the geometry remains intact and that the side boundaries of the geometry remain horizontal. This is achieved by identifying the start and the end points of the workpiece geometry and explicitly defining the x -displacement to be zero.

Once the required material removal and new location of the workpiece boundary points have been calculated, the tool feed rate (f) is factored in. For the purposes of this simulation f is assigned to the workpiece boundary (i.e. the tool coordinates

never change) by adding on the relevant y-displacement for that particular time-step.

$$\frac{\overrightarrow{dh}}{dt} = \frac{Jtn}{FM\rho} + f \tag{Equation 10}$$

Once the new coordinates of the workpiece boundary have been calculated, they can then be used to generate the new geometry for the FEA in the subsequent time-step.

3.5.4 Updating FEMLAB structure

In order to progress to the next iteration of the ECM simulation the new workpiece coordinates need to be translated back into a geometry that can then be used by the FEMLAB solver. The locations of the shifted workpiece coordinates now form a new boundary; however the distribution of these points may not be even along the length of the workpiece profile. To redistribute the points along this new profile, a spline function is fitted through the boundary coordinates, and the N points specified previously by the user are distributed evenly, by arc-length, along its length (Figure 30). The ECM simulation now contains an N -by-2 array of coordinates (x_N, y_N) distributed along our desired starting workpiece profile.

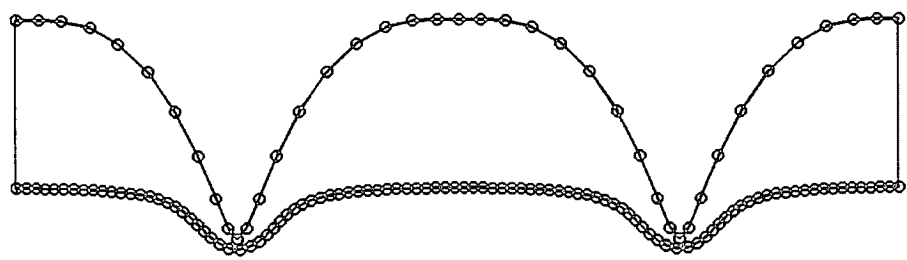


Figure 30: Equal distribution of points along the workpiece boundary based on arc-length

To reform the geometry, these points are once again connected together using straight-line FEMLAB geometries between them. The segmented workpiece

geometry profile is then recombined with the tool boundary and the side boundary geometries to form a closed subdomain that is suitable for use within the ECM simulation.

Again the boundary conditions are automatically applied to the correct geometric boundaries through a process of evaluation of the geometry, and the FEMLAB data structure is updated. This structure is fed back into the FEMLAB software where it is meshed and the solver initiated to give the solution for the next iteration of ECM modelling.

3.5.5 Simulation status display

Whilst the simulation is running the user is presented with an updating display of the geometry. In addition to the geometry status, a second display monitors the transient current during the simulation (Figure 31). The current is calculated through integration of the current density over the length of the workpiece boundary at each time-step using

$$I = \int_{l=0}^{l=L} \frac{J}{w} dl , \tag{Equation 11}$$

where L is the maximum arc-length of the workpiece profile. This visual feed back is designed to allow the user to monitor the simulation as it takes place to ensure that the inputs are producing satisfactory results. If an unexpected result is being displayed then the user can manually stop the simulation to reassess the parameter inputs.

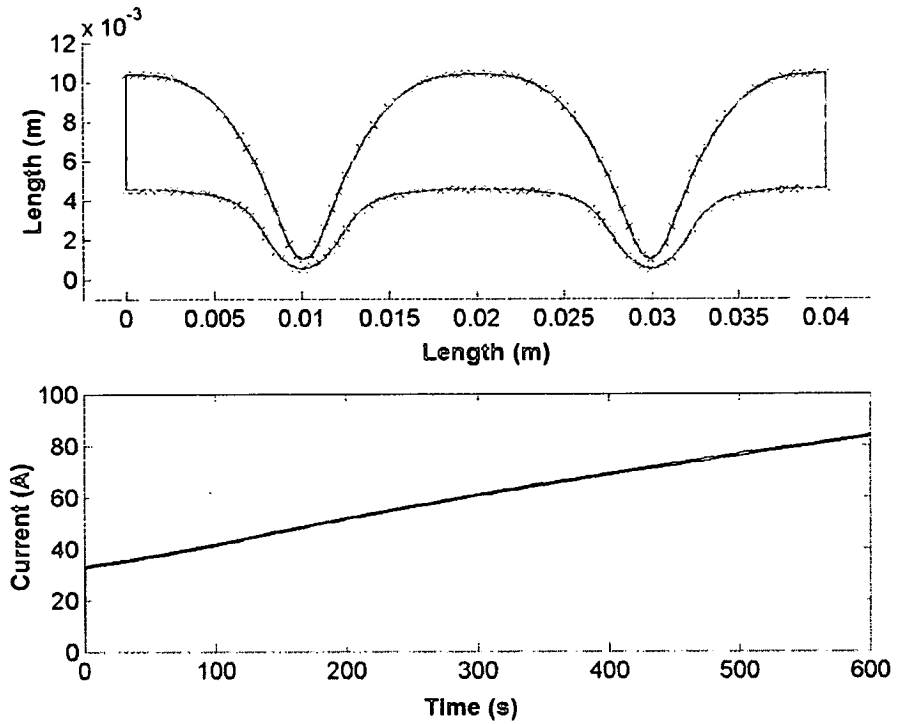


Figure 31: Sample output display to the user whilst the simulation is running. The top window shows the status of the geometry, the lower window is a plot of the current transient

3.5.6 Evaluating completion

As mentioned previously the user has the option of defining what exit condition is required for the simulation. The basic condition is to define a set period of simulated time, where the exit condition is:

$$\text{if (time} > \text{machining time)} \rightarrow \text{Exit}$$

This time-declaration condition is useful if a) the simulation is replicating a known machining run as a test for accuracy, or b) a non-equilibrium machining run is required and hence only a specific length of machining time is required.

An alternative exit condition is triggered by the current recorded during the simulation. This exit condition is most applicable if the user is unsure of the length of machining required to reach an equilibrium machining state. The test is based

on the difference between the current value in the current time-step and that of the previous iteration. If the current has not changed beyond a tolerance level defined by the user at the pre-processing stage of a simulation, then the simulation will register this in an exit array. Once the tolerance level has been met 20 times² the simulation will then stop running and results will be presented. It is necessary to register a number of occurrences of the tolerance level to ensure that no ‘false-equilibriums’ are identified. An example of this would be when machining with a large starting gap.

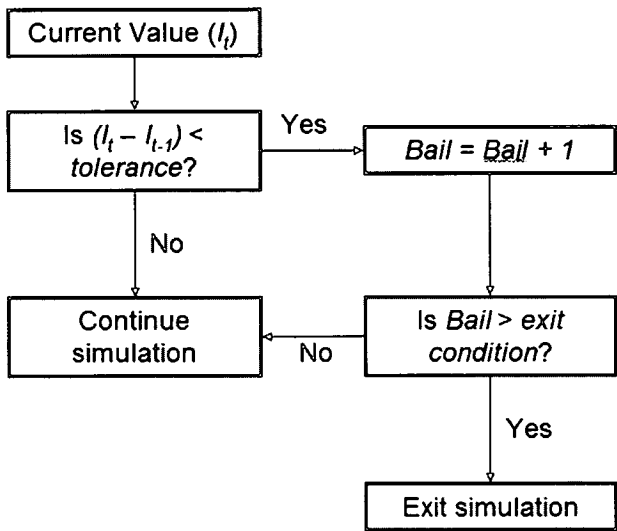


Figure 32: Flowchart describing the current based exit condition

Since there is a large body of transient data stored during the simulation the exit condition can, theoretically, be based on a number of different parameters. One such additional exit feature would be evaluating the closeness of the current workpiece geometry to that of a desired workpiece shape. By assessing the deviation between the coordinates of the workpiece boundary with that of the desired shape against a required geometry-accuracy tolerance, the exit condition for the simulation could be achieved.

² This is a default-value based on the author’s experience; it can be modified within the simulation scripts if an alternative result is required.

3.6 Post-processing Requirements

Throughout the simulation a number of parameters are stored for post-processing purposes. The main transient data sets collated are:

- Material Removal
- Current
- Current Density
- Workpiece coordinates and Geometry information
- FEMLAB data structures

When the simulation is initialised storage arrays for this data is created. During each iteration, the calculated data is indexed and logged based on the simulated time. This allows the user to access information on the simulation at any stage during the machining run – particularly useful for analysing non-equilibrium machining states.

3.7 Simulation Flowchart

For reference and clarity Figure 33 presents a flowchart of the entire simulation from the pre-processing stage until the simulation exits.

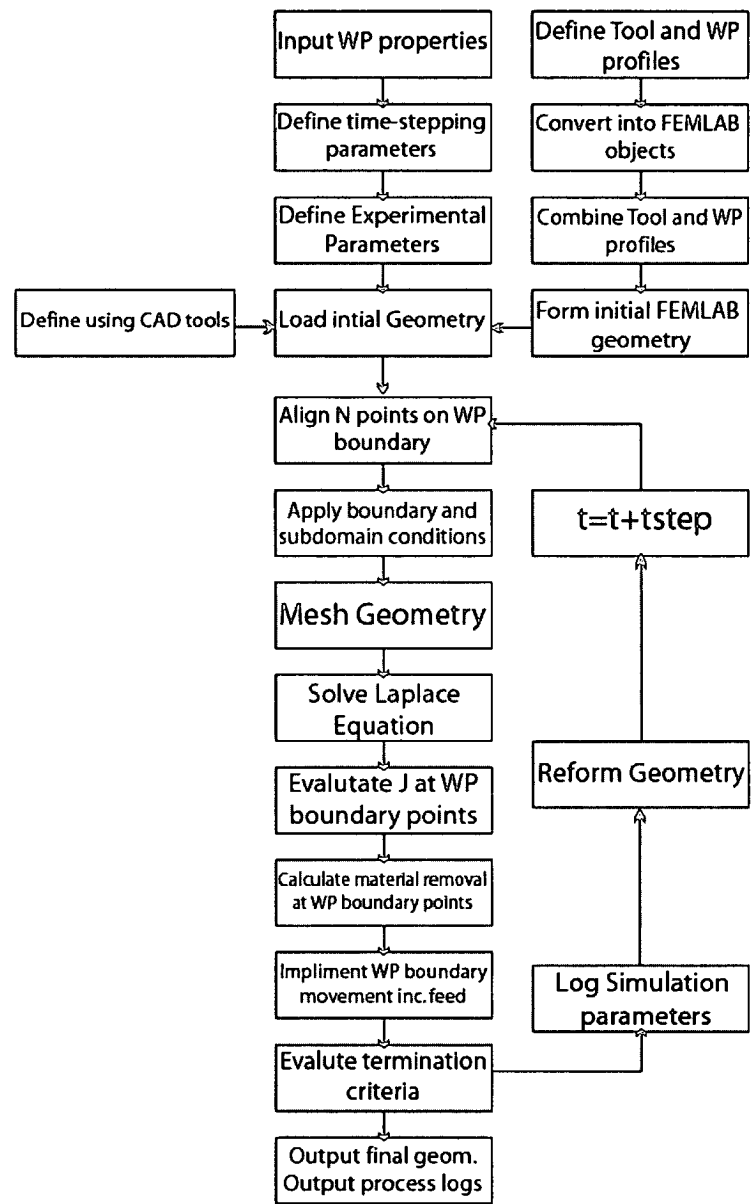


Figure 33: Flowchart describing the entire algorithm used for the time-dependent simulation of ECM ('WP' = workpiece)

3.8 Verification of Simulation: Machining a flat workpiece with double-cosine tool

3.8.1 Overview

The experiment presented here involved the machining of a flat workpiece using a ‘double-cosine’ tool shape. The workpiece material was Inconel 718, and machining surface dimensions $l = 0.04\text{m}$ and $w = 0.015\text{ m}$. Machining took place until equilibrium had been reached. The same machining process was then simulated using the ECM code. The parameter settings for both the experiment and the corresponding simulation were as follows:

<i>Component</i>	<i>Parameter</i>	<i>Value</i>
Material Properties	Atomic Mass	59.79
	Valency	2.9
	Density (kg m^{-3})	8228
	Overpotential (V)	3
Experimental Parameters	Feed rate (mm min^{-1})	0.5
	Starting gap (mm)	1
	Electrolyte Conductivity (S m^{-1})	16
	Applied Voltage (V)	16
Simulation Parameters	Time step (s)	10
	Total Time to Simulate (s)	2500

The simulation was performed on a PC with Dual Pentium 4 3.06GHz processors and 2Gb RAM.

3.8.2 Results

The simulation took 946 seconds to perform 250 iterations representing the 2500 seconds of machining ($0.26 \text{ iterations sec}^{-1}$). Figure 34 shows the final output from the simulation. The upper image is the equilibrium shape profiles of the geometry, the lower the current transient during machining.

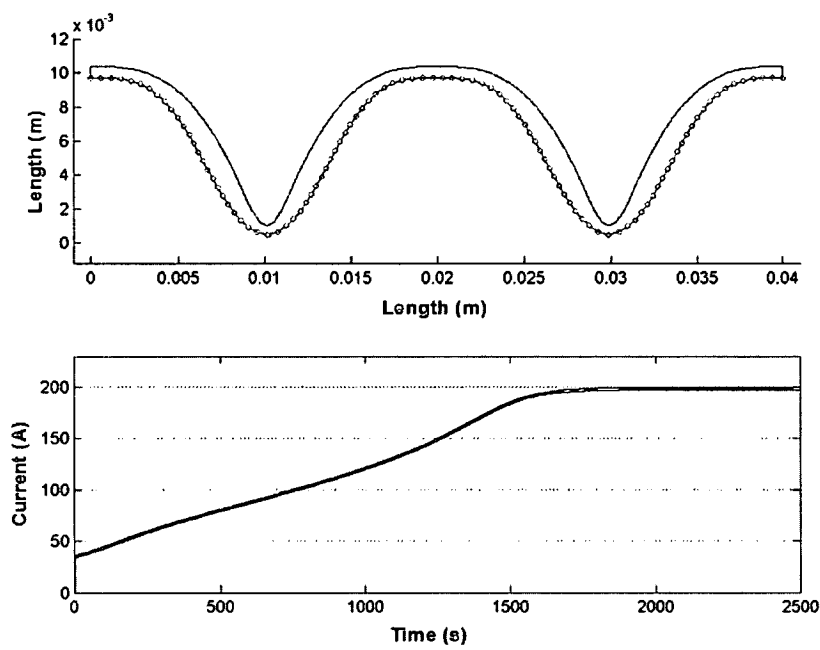


Figure 34: Output display from the machining to equilibrium of an Inconel 718 workpiece

As expected as the machined profile approaches equilibrium, the current being recorded levels off. The equilibrium current for this simulation was calculated as 198 A.

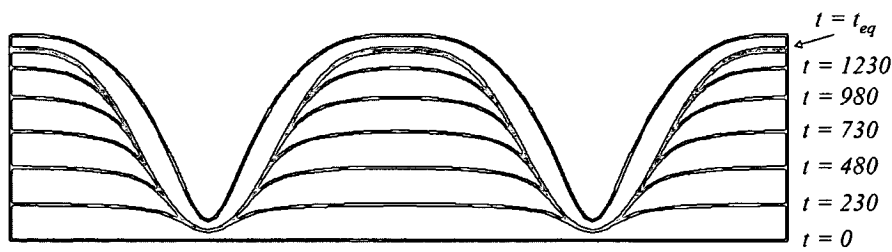


Figure 35: The evolution of the workpiece boundary (time in seconds)

Since the simulation is time-dependent, the evolution of the workpiece profile can be observed. Figure 35 shows a plot of the workpiece boundary as it evolves over time. Finally, Figure 36 shows a comparison between the simulated and experimental³ equilibrium profiles. The profile of the experimental surface was determined through use of image processing tools that allow a series of points to be manually distributed along the length of the upper surface of the workpiece. By calibrating the system against a known length (in this case that of the workpiece width), the resulting profile of points can be used to form a profile that can be compared against the simulated profile.

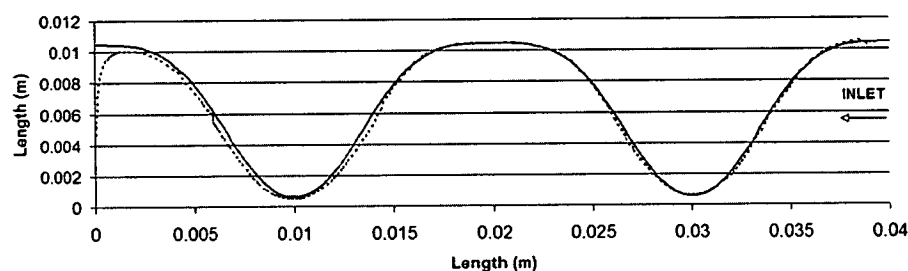


Figure 36: Comparison of simulated (—) and experimental (---) workpiece profiles at equilibrium

An qualitative look at the profiles shows that there appears to be a close correlation between the virtual and the real machined profiles with a slight deviation towards the end of the flow path. It is believed that this deviation is the result of temperature increases within the electrolyte during machining.

The magnitude of this deviation can be assessed through analysis of the material removal between the experimental and simulation runs. Figure 37 shows the location of five points where the thickness of the machined workpiece was measured. At the same corresponding points on the simulated workpiece, the total material removal was extracted and the results compared (Figure 38).

³ The experimental set-up used by the ECM group is discussed in more detail in Chapters 5 and 6.

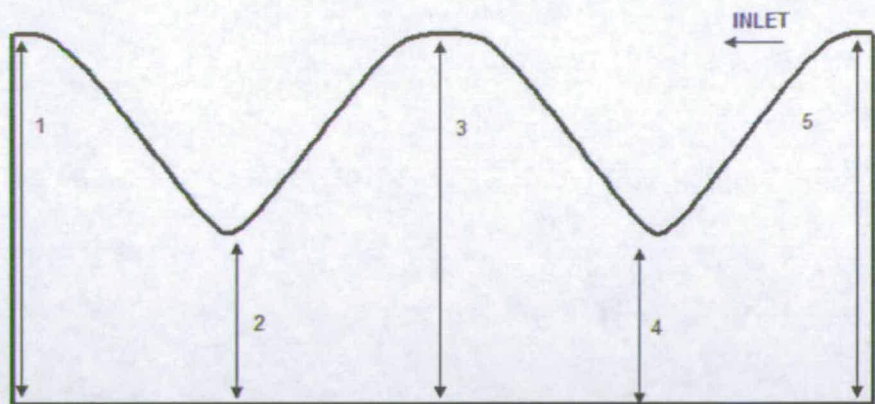


Figure 37: The location of 5 measurement points where workpiece thickness was determined

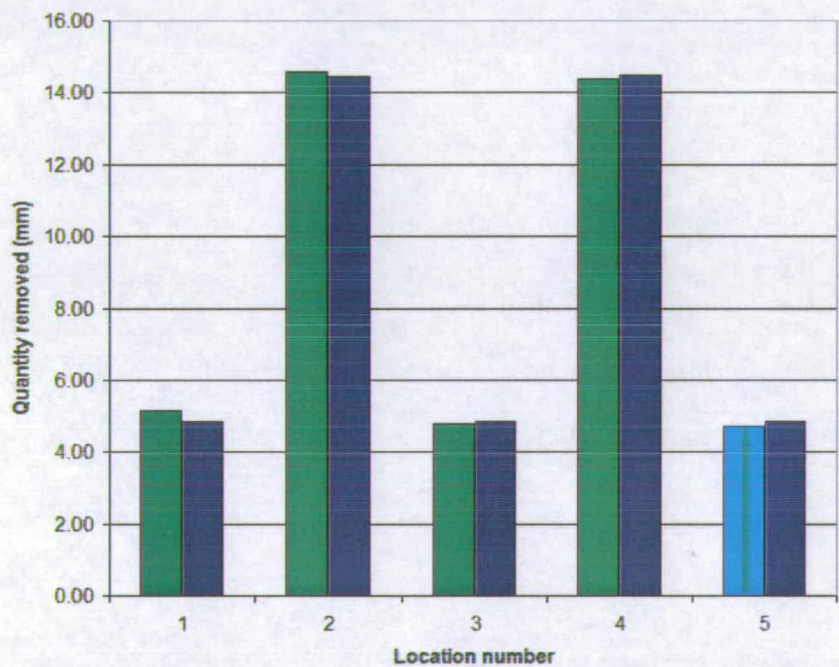


Figure 38: Graph showing the material removal comparison between experimental (■) and simulation (■) results

Further analysis of these results give the deviation between simulation and experimental material removal values. The maximum deviation was at the electrolyte outlet and had a magnitude of 0.31mm.

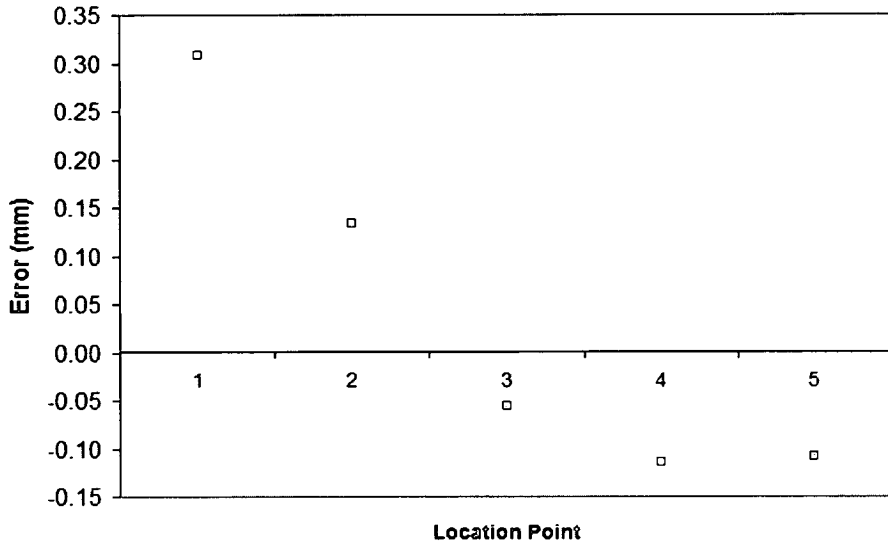


Figure 39: Deviation between simulation and experimental material removal results at the 5 measurement locations

3.9 Conclusions

This chapter has presented the methodology and rationale behind the development of a time-dependent, finite-element based, simulation tool. Results have been presented showing the evolution of a complex, double-cosine, tool shape machining a flat workpiece. The accuracy of the simulation has been assessed through comparison against experimental results. The time-dependent nature of this simulation means that workpiece profiles can be analysed even at non-equilibrium machining conditions, something particularly applicable to many industrial ECM manufacturing processes. At this stage the simulation is performed under ideal conditions, though in Chapters 5 and 6 the introduction of a parameterised overpotential model is discussed. Before advancing to those simulation modifications, the following chapter assesses the applicability and versatility of this ideal simulation to a number of industry specific machining scenarios.

Chapter:

4 Industrial Applications of the Simulation

This chapter's emphasis is on adapting the simulation presented previously to represent real-life industrial ECM methods. Starting with machining non-flat workpieces, the chapter then discusses the simulation of ECM using alternating current. Finally the simulation of a combined tooling arrangement similar to those used in the manufacturing of turbine blades is presented. For each of the adaptations the modifications required to the simulation code is discussed and results are presented.

4.1 Introduction

Following on from simulation work presented in the previous chapter this section presents further adaptations of the ECM simulation that has been developed. The emphasis of this chapter is to look at the flexibility of this simulation in an industrial environment by demonstrating different variations of the ECM process often used in the fabrication of parts. Much of this work has been developed as a direct result of the need of Philips Aerospace to use this simulation work to mimic the ECM systems they have in place.

The three adaptations to be presented and discussed are:

- Machining non-flat workpieces
- ECM using alternating current
- Machining using more than one tool electrode

For each adaptation the modifications that are required to set-up the simulation are discussed. This is then followed by a sample simulation using the methodology defined.

4.2 Machining non-flat workpieces

In the previous chapter the simulation developed started with a flat workpiece surface. Often in industry ECM is applied as a finishing tool to create smooth and accurate parts. Initial machining will often be carried out using conventional techniques such as high speed drilling or grinding to create the rough outline of the desired shape. In these cases the ECM workpiece is unlikely to be in a flat and smooth, starting condition. Scalloping, or roughness of the surface, will often be present and it is of critical importance that the operator knows how long to ECM a workpiece so as to remove the rough working scalloping without machining away too much of the main workpiece material (Figure 40).

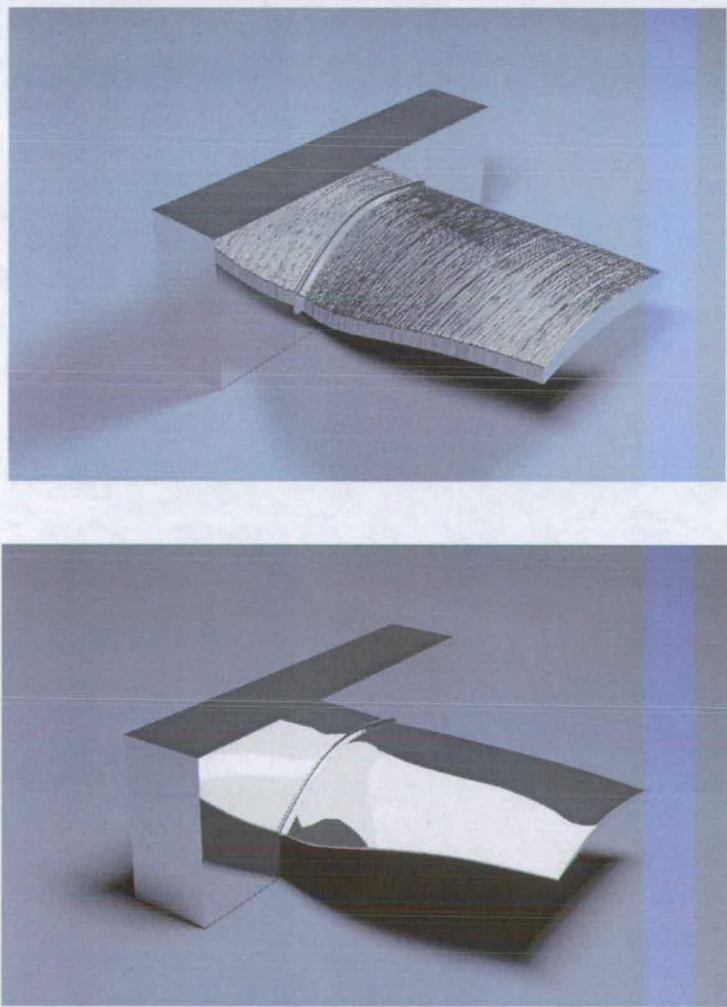


Figure 40: Rendered images of a scalloped and finished turbine blade.

This section presents the adaptations required and the methodology implemented for the simulation of machining of a scalloped workpiece machining.

4.2.1 Modifications required

In order to implement a non-flat starting workpiece profile requires minor modifications to the pre-processing section of the code. The main changes are the input of a non-flat geometry boundary for the workpiece and alterations to the starting gap algorithm.

A non-flat geometry boundary can be created either in a CAD package and imported directly into the FEMLAB software for use in the simulation as previously described in Chapter 3. Alternatively a series of points can be automatically generated based on a user-defined function that distributes them to form the boundary profile of a non-flat workpiece (Figure 41).

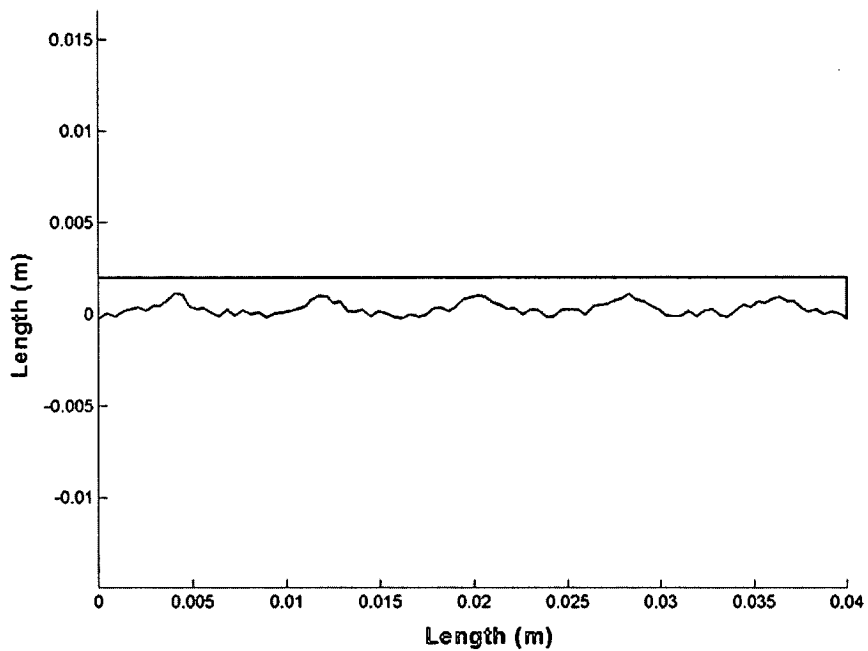


Figure 41: A semi-random workpiece generated using a function within the pre-processor

The starting gap algorithm needs to be altered to ensure that upon geometry generation the tool profile does not intersect the workpiece boundary. When simulating machining with a flat workpiece the lowest point of the tool profile was located above a datum defined by the y-coordinate of the flat workpiece. For a non-flat starting workpiece the algorithm needs to identify the highest point on the starting workpiece profile and orientate the tool so that the distance between this point and the lowest point on the tool is the defined starting gap (Figure 42).

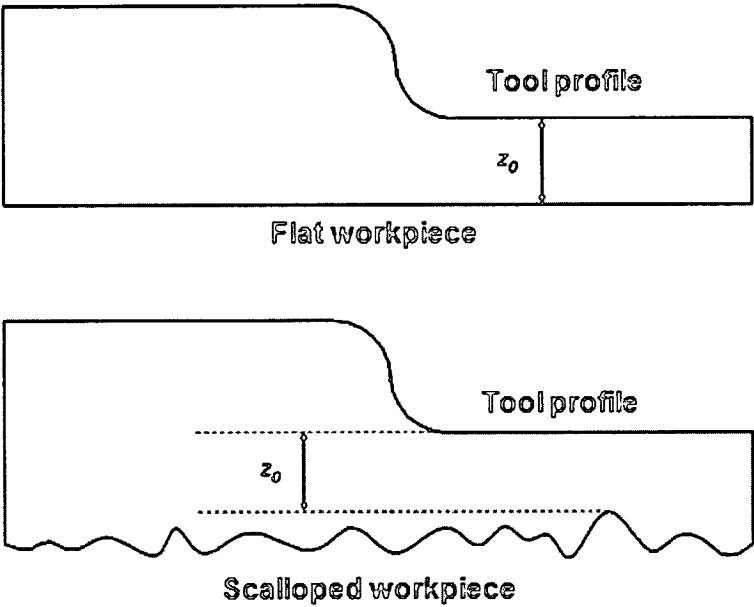


Figure 42: Starting gap (z_0) for a flat and a scalloped workpiece

4.2.2 Setting up a rough workpiece simulation

The example shown here is of the machining of a 40 mm x 15 mm titanium 6-4 workpiece that has undergone a process of CNC milling to shape it into a starting form. Figure 43 shows the top surface of a sample workpiece supplied by Philips Aerospace. From this image it is apparent that the scalloping on the surface of this workpiece follows a relatively repetitive pattern – consistent with the repeated tool paths found in CNC machining. To recreate this surface in the ECM simulation the second, user-defined function, method was implemented. This required a function, or a series of points that could be repeated, to define the rough nature of this

surface. In order to accurately mimic this surface, a Zygo machine was used to scan a portion of the surface, resulting in a map of height data from the workpiece (Figure 43). The surface roughness of the scalloped workpiece was measured using a Zygo NewView 100, produced by the Zygo Corporation (Laurel Brook Road, Middlefield, CT 06455-0448.). This scanning white light interferometer allows surface topography measurements with a lateral resolution of approximately 0.5 μm and a vertical resolution of 0.3 nm.

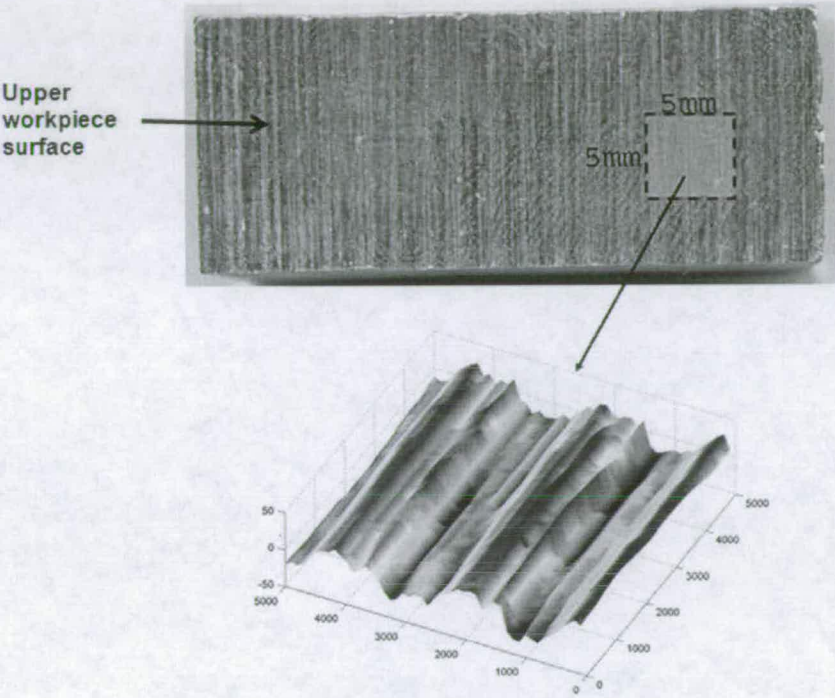


Figure 43: A top down view of the workpiece. The roughness of the surface can be seen as lines running across the width. The area indicated is the region of the workpiece surface scanned using the Zygo. The bottom image shows the output topography of the 5 x 5 mm area. Units are in microns.

A cross-section of this height map was taken to produce a set of points that could be used as an input into the simulation (Figure 44). Since the Zygo machine is limited in the area that it can scan only a small 5 x 5 mm area can be analysed. Consequently the resulting point curve needs to be repeated over the length of a workpiece.

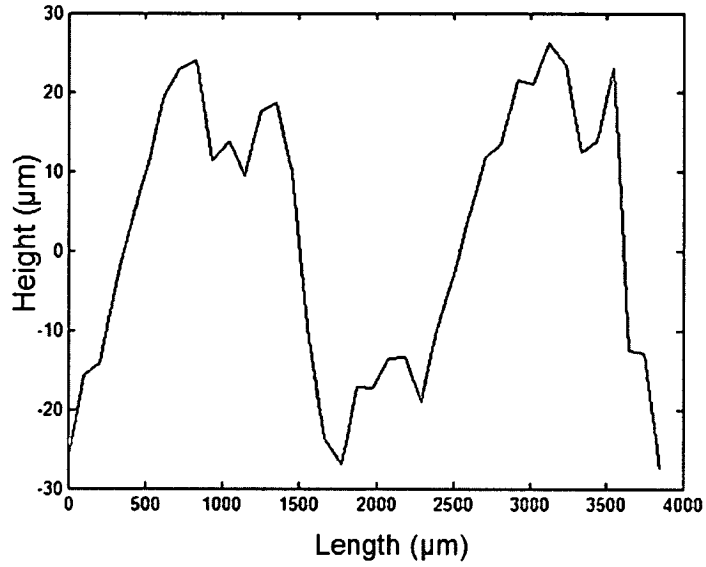


Figure 44: Cross-section of the height map

The point data generated was inputted into the pre-processing area of the code at the point where the workpiece was previously generated as a single flat line. To allow the repetition of this profile, the user inputs have been augmented so that they now can define the length of their workpiece, the number of scallops along the workpiece profile required (n_s) and the maximum height (h_s) of the scalloping. These last two additions are based on scaling the original data to match the required inputs. Figure 45 shows the starting geometry for a scalloped surface with $z_0 = 1\text{mm}$, $h_s = 1\text{mm}$, and $n_s = 20$.

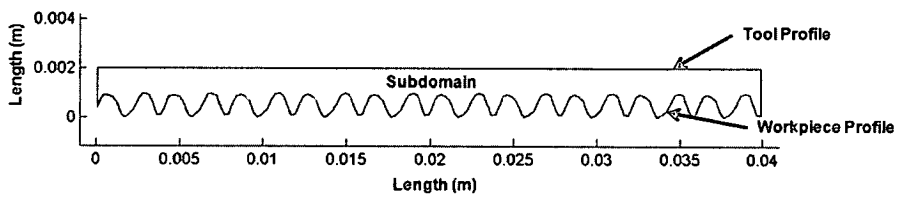


Figure 45: Input geometry profile for the scallop simulation. The rough lower surface is that of the workpiece, whilst the straight, upper surface represents a flat tool. The subdomain is shown in grey.

Once the workpiece boundary points are defined, the code automatically converts the profile into a boundary object and combines it with the tooling profile. The final change in this simulation was made to the number of points a user inputs to define the surface of their workpiece - the boundary points where material removal is evaluated. Since we require X points to define the boundary if we choose $N < X$ for our boundary points we will not achieve a realistic material removal of this profile, consequently if the user inputs a value of $N < X$ the simulation will automatically override this and set $N = X$. If $N > X$ then this value of N is used.

4.2.3 Sample Results

Simulation Set-up

This example involves the machining of a rough workpiece using a flat tool. The rough workpiece was generated by repeating a pair of scallop profiles along the length of the workpiece. The maximum height of the scallop was 2 mm. The workpiece dimensions were $l = 0.04$ m and $w = 0.015$ m. The workpiece material was titanium 6/4. The simulation parameters were:

<i>Component</i>	<i>Parameter</i>	<i>Value</i>
Material Properties	Atomic Mass	45.8
	Valency	4
	Density (kg m ⁻³)	4418
	Overpotential (V)	5
Experimental Parameters	Feed rate (mm min ⁻¹)	0.5
	Starting gap (mm)	1
	Electrolyte Conductivity (S m ⁻¹)	15
	Applied Voltage (V)	15
Simulation Parameters	Time step (s)	10
	Total Time to Simulate (s)	300

The simulation was performed on a PC with Dual Pentium 4 3.06GHz processors and 2Gb RAM.

The full length input geometry is shown in full in Figure 46 with a section showing the detail of the scalloping in Figure 47.

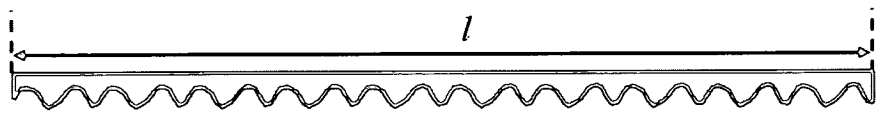


Figure 46: The input geometry used for the simulation. The rough workpiece is shown as the lower boundary, and the flat tool as the upper. The length, l , equals 0.04 m.

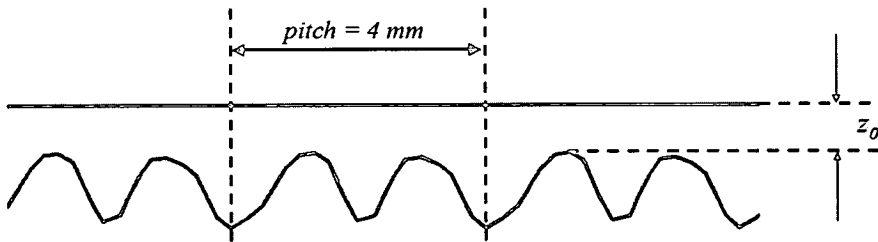


Figure 47: Detailed view of a section of the input geometry. Shown is the pitch of the scalloping, and the point from which the starting gap is measured.

Results

The total simulation time was 232 seconds for 30 iterations ($0.13 \text{ iterations s}^{-1}$), representing 300 seconds of actual machining. In Figure 48, the machining profile of the workpiece is shown at various stages in time. As the workpiece approaches the tool, the height of the scalloping is reduced, until at equilibrium the workpiece is flat. Since this type of machining is used in the smoothing of parts, the material removal is of importance to ensure that only the scallops are removed.

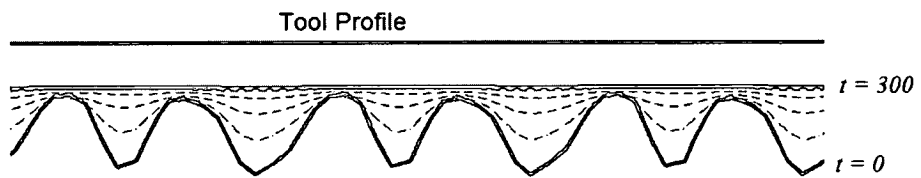


Figure 48: Machining of the scalloped workpiece surface as it approaches a flat tool

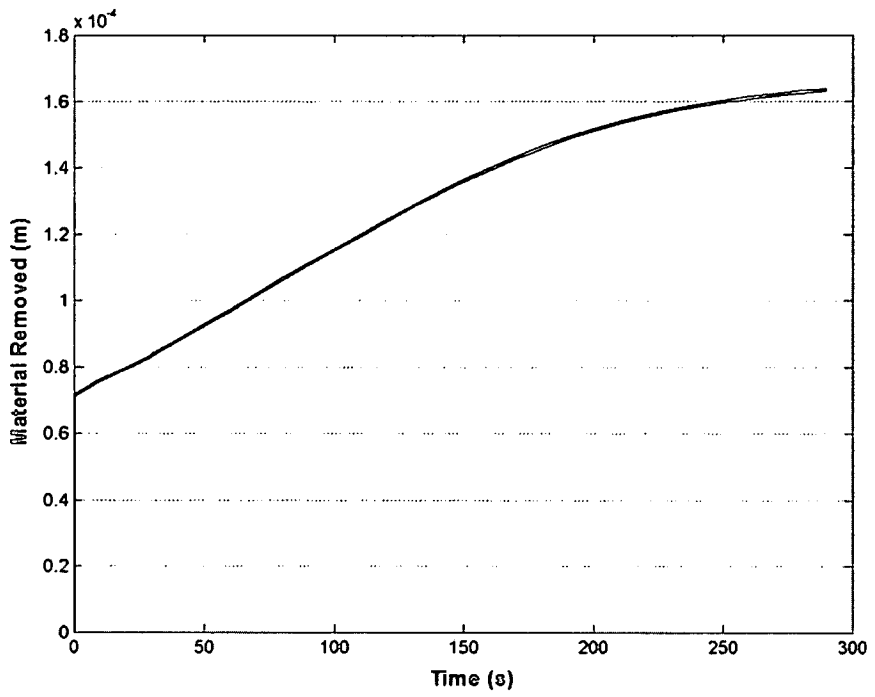


Figure 49: Material removal over time for the machining of a scalloped workpiece

As a demonstration of the output capabilities of the simulation developed, Figure 49 shows the total material removed from the workpiece as a function of time.

4.3 Alternating Current ECM

Alternating current (A.C.) ECM is another commonly used machining technique used in industry. As is suggested by the name, A.C. ECM uses a pulsed current in place of D.C. to drive the material removal. The rationale behind such a system is to allow the debris and hydrogen generated by the electrolytic process to be removed between the pulses of current, alleviating the effects of conductivity changes within the inter-electrode gap. The challenge to using this type of system is maintaining a suitably large inter-electrode gap so that sparking or, in a worst-case scenario physical contact between tool and workpiece, does not take place. Establishing the correct pulse length, pulse magnitude and feed rate is important in this type of system to ensure that these problems do not manifest.

4.3.1 Modifications required

In order to simulate the machining of a workpiece using the A.C. method it is necessary to modify the way the boundary conditions are applied during a simulation. Presently the simulation uses an applied voltage that remains constant throughout the duration of the simulation. This boundary condition needs to be altered so that the applied voltage represents the on-off pulse of the A.C. system. Typically an A.C. pulse will fluctuate rapidly over time – typically in the order of milliseconds. The principal issue is that fluctuations on this order of magnitude mean that many will occur during a single ECM simulation time-step. One solution is to run with a time-step size that allows a number of iterations during the duration of the pulse, though this will result in a lengthy simulation time. The alternative approach is to take an average of the applied voltage over a larger time-step based on the total on and off periods. Both these methods are discussed below, however they share the same requirement that a pulse needs to be defined by the user during the pre-processing stage. This is implemented by the addition of two input commands that require the user to declare the pulse on and the pulse off duration.

For the purposes of these examples a square-wave function is used to define the A.C. waveform. Alternative approaches can be implemented so that a non-square wave, for example a sinusoidal wave, can be used.

4.3.2 Small time-step (STS) approach

Using the STS approach the boundary condition to be applied in the simulation needs to be assessed using an algorithm that states whether the pulse is on or off in that particular time-step. This is achieved through use of a Boolean function.

The user is required to define the parameters of an individual A.C. pulse that will be looped repeatedly throughout the duration of the simulation. The calculation for the number of individual wave forms to be evaluated is based on the total machining time used in the simulation. During each iteration the processor assesses whether the pulse is in an ‘on’ or ‘off’ state based on the current time. If this evaluation returns a positive, i.e. the pulse is in the ‘on’ phase, then the boundary condition of the workpiece is assigned the applied voltage, if it is ‘off’ then the applied voltage is set to zero and no material removal will occur.

Demonstrated below is an output from a simulation using the STS method. The simulation for this is a flat workpiece and tool combination. The A.C. pulse was a square wave with a cycle time of 0.6 seconds.

The other simulation parameters were:

<i>Component</i>	<i>Parameter</i>	<i>Value</i>
Material Properties	Atomic Mass	45.8
	Valency	4
	Density (kg m ⁻³)	4418
	Overpotential (V)	5
Experimental Parameters	Feed rate (mm min ⁻¹)	0.5
	Starting gap (mm)	1
	Electrolyte Conductivity (S m ⁻¹)	15
	Pulse on Voltage (V)	15
	Pulse on (s)	0.12
	Pulse off (s)	0.48
Simulation	Time step (s)	0.004

Parameters		
	Total Time to Simulate (s)	2.4

The simulation was performed on a PC with Dual Pentium 4 3.06GHz processors and 2Gb RAM. Total simulation time was 2,262 seconds for 600 iterations (0.27 iterations sec⁻¹) describing 2.4 seconds of machining.

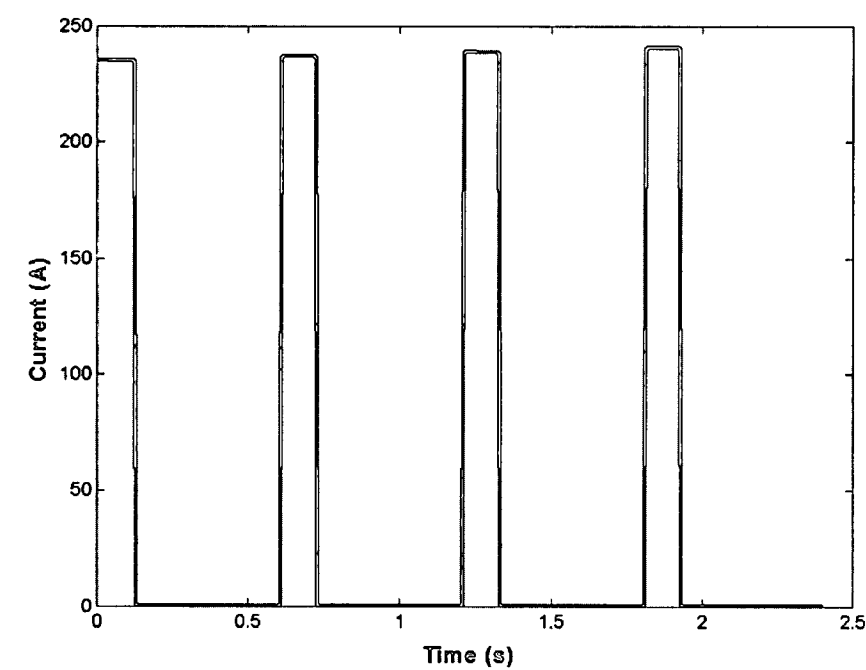


Figure 50: Current transient for A.C. pulse simulation

Figure 50 displays the current transient for the STS method of simulating ECM using A.C. It demonstrates how at specific times the applied voltage is either on or off. Using this time-dependent, SLS method enables a closer examination of some key parameters during ECM. In Figure 51 the variation in the inter-electrode gap during the simulation can be observed. Simulations using this method could be used in a more detailed examination of the processes taking place during pulse on and pulse off times.

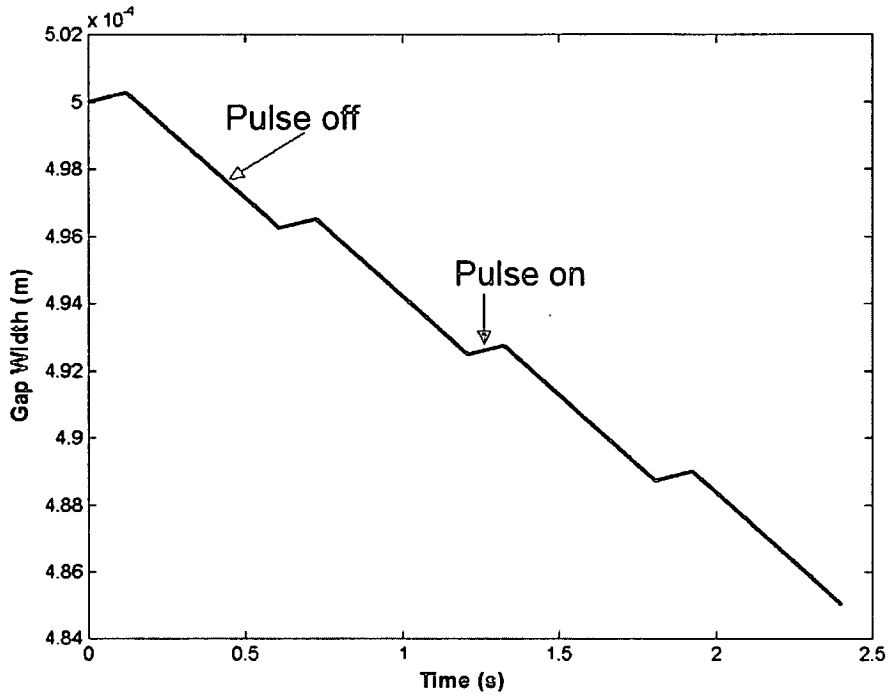


Figure 51: Variation in gap width over time when machining using A.C. The gap increases when the pulse is on since material removal takes place at a rate greater than the feed.

4.3.3 Large time-step (LTS) approach

The previous method required a time-step with duration in the order of milliseconds. For industrial applications simulating using this approach is time-consuming and many iterations need to be performed to complete an entire machining run e.g. for a 20 minute machining run using the example outlined in 4.3.2, 300,000 time steps are required. In order to accelerate the simulation using A.C. conditions the LTS approach can be used. This method works on the principal of averaging the on and off time of an A.C. pulse over a larger time-step, in the order of seconds. Since machining, i.e. during the on-pulse, takes place for a percentage of a single duty cycle, this percentage can be applied over a larger period of time.

One approach to applying this would be to scale the up the A.C. pulse wave so that it lasted for a number of the larger time-steps. For example, if using the STS method with a time-step of 25 ms to simulate a pulse with an on-time of 33% of a single A.C. waveform that lasts for 300 ms, this results in 4 time-steps where the

pulse is on. Scaling this up to a large time-step, say 5 seconds, will mean that the pulse on-time becomes 20 seconds and the pulse-off time equals 40 seconds. The downside to this approach is that there will be a lengthy period of time where no machining occurs. If the feed rate is great enough this can result in the collision of the workpiece surface and the tooling surface, resulting in the subdomain geometry losing its integrity and subsequently the breakdown of the simulation.

A more robust method of implementing this A.C. waveform over the length of a simulation is to use the pulse on/off ratio to modify the applied voltage. This modified voltage can then be used for the duration of the simulation as the workpiece boundary condition meaning that machining always occurs and subsequently the chances of a geometry breakdown are greatly reduced. In order to scale the applied voltage Equation 12 is used to define the applied voltage for use during the simulation.

$$V_{t\ A.C.} = \frac{pulse_{on}}{pulse_{total}} V_{t\ D.C.}$$

Equation 12

The results of a gap comparison between simulating using the D.C. method and the LTS A.C. approach are in Figure 52. The parameters of the simulations were:

<i>Component</i>	<i>Parameter</i>	<i>Value</i>
Material Properties	Atomic Mass	45.8
	Valency	4
	Density (kg m ⁻³)	4418
	Overpotential (V)	5
Experimental Parameters	Feed rate (mm min ⁻¹)	0.5
	Starting gap (mm)	1
	Electrolyte Conductivity (S m ⁻¹)	15
	Pulse on Voltage (V)	15
	Pulse on (s)	0.12

	Pulse off (s)	0.48
Simulation Parameters	Time step (s)	10
	Total Time to Simulate (s)	190

As expected the simulation using the A.C. waveform as an input results in a smaller final gap.

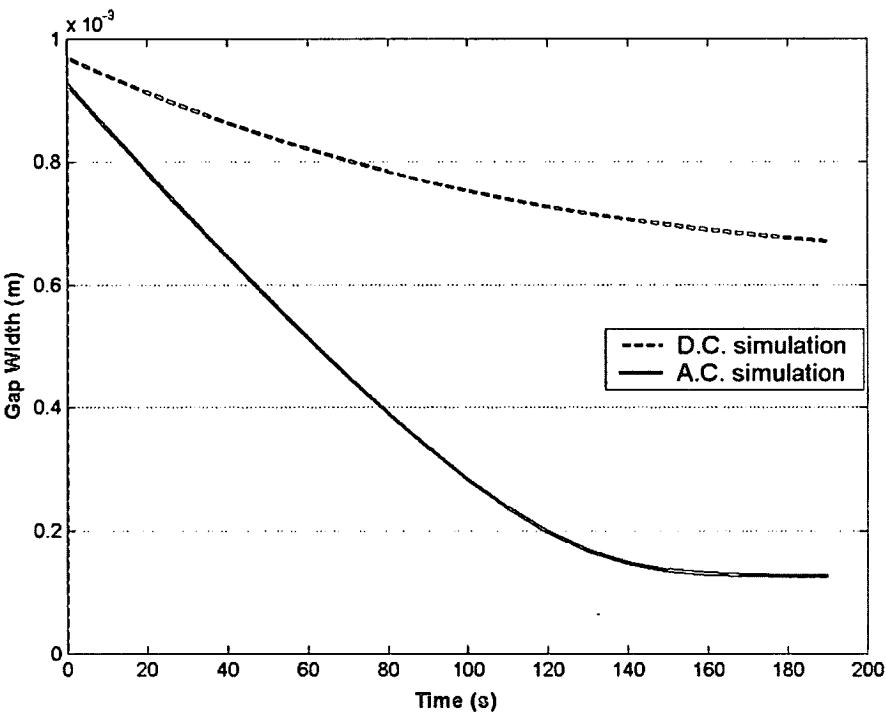


Figure 52: Comparison of variation in gap width over time for a D.C. and A.C. simulations using a flat workpiece

4.3.4 Choice of method

The choice of method to use when simulating using A.C. approach is dependent upon the results that are needed to be observed. Clearly if you are interested in the effect of the A.C. ECM at a pulse scale then the STS approach should be used, conversely if you are looking for a simulation of a large machining run then the LTS method can be deployed.

The LTS method however is limited if the user wishes to observe the effect of the pulsed current on different process parameters such as hydrogen generation. When the pulse is 'off' there is no machining occurring and consequently the by-products of electrolysis are ejected from the inter-electrode gap via the electrolyte flow. A more detailed study of the effects on the conductivity and the machining surface would be difficult using the LTS method as the subtlety of the changes are removed by the scale of the time-step.

4.4 Combined tool ECM

This is a form of ECM that is often used in the fabrication of turbine blades in the aerospace industry. It is similar to the die-sinking ECM simulations presented previously; however in this scenario there are two tooling surfaces simultaneously machining a workpiece. Figure 53 gives a cross-sectioned schematic of the orientation of the tools and workpiece for the combined tool ECM of an aerofoil shape.

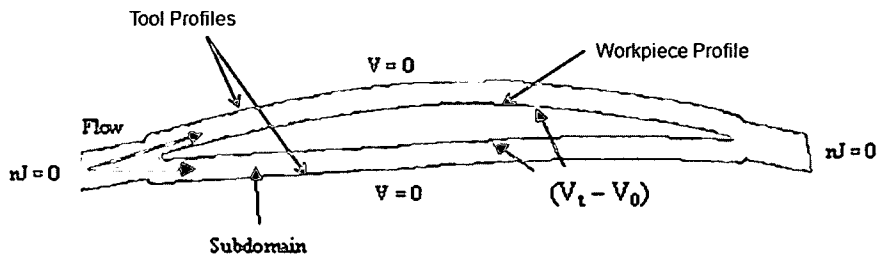


Figure 53: Cross-sectioned view of an aerofoil blisk undergoing combined tool ECM

Tool design for this type of machining is challenging since equilibrium machining will never be reached. The effect of this is most apparent at the trailing and leading edges of the workpiece where the curved surfaces will constantly recede back during machining. It is of critical importance to be able to judge exactly how long ECM should be applied to such workpieces so as to maintain the correct level of accuracy for the finished component.

4.4.1 Modifications required

Implementing a combined tool machining system to the current ECM code requires alterations to be made to the techniques used to represent the geometry. A number of changes need to be made to allow the automated simulation of this dynamic process. The key areas that need to be modified are:

- The identification of tool and workpiece boundaries
- The definition of material removal points along the workpiece boundary
- The application of the feed rate

For the purposes of explanation these modifications will be explained using the generic geometry outlined below. Though it is a generic shape it is representative of a trailing edge of a turbine blade and the same techniques can be used in an industry specific machining application.

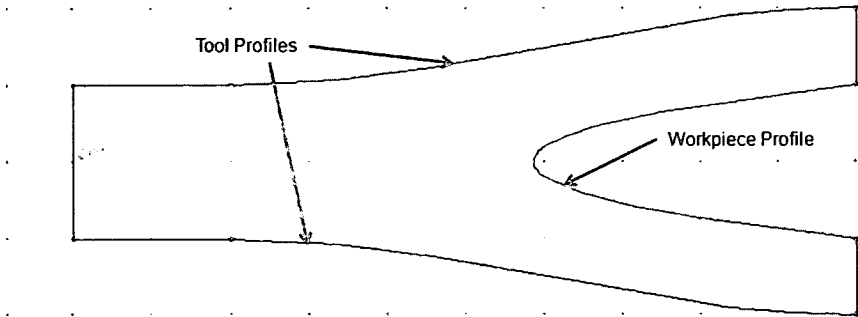


Figure 54: Sample geometry used in the simulation

Identification of workpiece and tool boundaries

Previously the tool and workpiece boundaries lay above and below each other respectively, this simplified the algorithms required for identification in the ECM code. In the combined tool simulation, the FEMLAB ID system can again be exploited, though this time it is the tool boundaries that are identified first. By assessing the normal of each of the boundary sections the side boundaries can also be identified. Finally the workpiece boundary ID's are obtained through implication.

Definition of material removal points

In the standard simulation using one-tool and one-workpiece the number of points where material removal was to be calculated, and were defined in the pre-processing stage, remained constant throughout the simulation. This was a valid approach since the global width of the workpiece remained the same during the course of the simulation, and though the arc length would vary provided a sufficient number of points were defined a suitable geometry would always be formed. As discussed above the workpiece in the combined tool simulation will be

constantly receding and an equilibrium machining condition will never be reached. Additionally the workpiece boundary displays a high degree of curvature in places and so the distribution of points to successfully represent the machining in these areas needs to be non-linear. This requires a more adaptive and reactive point definition algorithm to be used.

In the pre-processor the user will still define the starting number of points required to be aligned over the length of the workpiece boundary. This is the initial number of points that will be used to describe the surface. To distribute the points a spline is fitted along the boundary sections that make up the surface of the workpiece. The resulting curve is differentiated to give the curvature of the workpiece boundary along its length. Using this curvature information, different numbers of points are allocated to different workpiece locations based on a percentage basis. The allocation process operates by calculating the range of curvature present on the surface and the assignment of more points to those areas of high curvature. The number of points assigned to high curvature areas is based on a percentage of the total number of points defined. The example shown in Figure 55 demonstrates how 50 points are distributed along our sample workpiece profile. In this example 60% of the points are located in the highest 30% curvature range calculated in the spline. Successive points are distributed evenly along the different sections, the spacing of which is governed by the number of points and the length of the workpiece region.

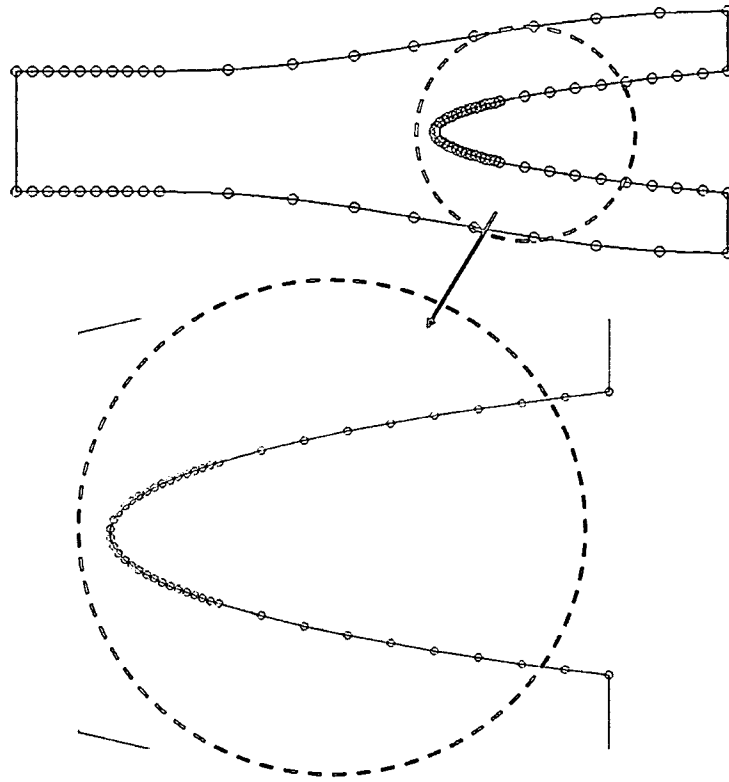


Figure 55: Arrangement of points along workpiece boundary

One of the constraints of the ECM simulation is that during material removal calculations neighbouring points should be restricted from crossing over each other. Previously this was achieved through limiting the maximum distance that the points could move. In this example combined tool simulation the trailing edge has been allocated the majority of the points, however it is also this region that is most susceptible to shape change. During machining the leading edge of the workpiece profile will be machined back and also become thinner. Consequently the arc-length of this region will become shorter with a higher degree of curvature, resulting in a closer spacing of the defining boundary points. To prevent regularly point cross-over the number of points orientated on this boundary needs to be reduced.

The algorithm developed to enable this is based on the proximity of each boundary point to its neighbours. Based on the length of the region with a finer distribution of particles, a minimum spacing parameter is calculated. Following the material

removal calculation, each point within the simulation is checked to see if one of its neighbouring points lies within this minimum spacing distance along the arc-length. If so, then it is removed from the simulation, and the total number of points defining the profile is reduced by 1. Once this algorithm is complete, the spline-point distribution algorithm is performed again to produce the new point distribution along the workpiece profile.

Application of the boundary feed rate

Since we have two tooling surfaces we need to define the feed so that it acts on both of the tool profiles. The standard die-sinking ECM simulation combines the tool movement with the material removal so that the workpiece boundary points are given a uniform translation to account for the approaching tool. In this example the feed rate needs to be applied to the tooling surfaces. Having identified the workpiece boundary for the previous section, through implication the simulation will know which boundaries form the tool profiles. However, it is necessary to break this association down a further level to identify which boundaries form the upper and the lower tool profiles. This is achieved using similar connectivity methods as described in previous sections (based on knowing the starting boundary numbers for the left hand end of each boundary). Once the boundaries have been identified the feed rate can be applied, ensuring that the direction of the feed is correct to produce an inwards motion.

4.4.2 · Example Simulation

Simulation Set-up

The example shown is the machining of the demonstration case. The workpiece used was a generic shape, though the machining process is similar to that of a trailing edge of a turbine blade. The workpiece material was titanium 6/4. The simulation parameters were:

<i>Component</i>	<i>Parameter</i>	<i>Value</i>
Material Properties	Atomic Mass	45.8
	Valency	4
	Density (kg m ⁻³)	4418
	Overpotential (V)	5
Experimental Parameters	Feed rate (mm min ⁻¹)	0.5
	Starting gap (mm)	2
	Electrolyte Conductivity (S m ⁻¹)	20
	Applied Voltage (V)	15
Simulation Parameters	Time step (s)	5
	Total Time to Simulate (s)	240

The simulation was performed on a PC with Dual Pentium 4 3.06GHz processors and 2Gb RAM.

Results

The total simulation time was 220 seconds for 48 iterations ($0.22 \text{ iterations sec}^{-1}$), representing 240 seconds of actual machining. Figure 56 shows the machining surface of the workpiece over time during the simulation. The front tip of the workpiece visibly recedes over the course of the machining run. The motion of the tool profiles is also shown.

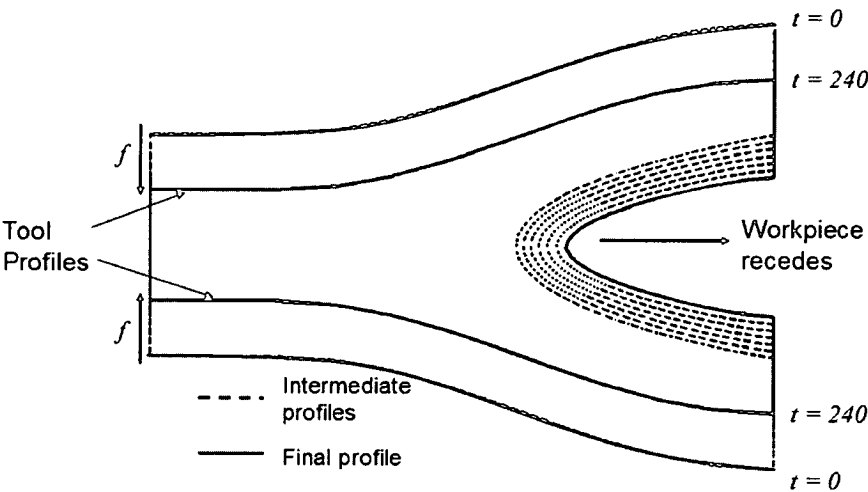


Figure 56: The evolution of the tools and workpiece during combined tool simulation (t in seconds)

4.5 Conclusions

The purpose of this chapter was to demonstrate the versatility of the time-dependent simulation presented in Chapter 3. In particular, the ability to modify the simulation to suit specific industrial requirements has been shown. This simulation adaptability is vitally important if simulation techniques are to be used as a successful pre-machining, industrial, tool.

At this stage, the simulations presented are based on the assumption of ideal machining conditions. This assumption rarely holds during actual machining, and consequently a more accurate simulation will include parameter variation. The focus of the next section of work is based on the development and inclusion of a parameterised model of the overpotential during ECM.

Chapter:

5 Developing a Non-Ideal ECM Simulation

Part A: Measuring Time-Dependent Overpotential Data

This chapter presents the experimental procedure used to measure the variations in overpotential during ECM. A unique ultrasound method is presented and compared against the existing chronoamperometric method. This is followed by a close analysis of the behaviour of the current-overpotential relationship, with a view of producing a parameterised model that can be implemented into a simulation of the ECM process.

5.1 Introduction

The simulations described in the previous section are based on the assumption that the overpotential (V_0) remains constant throughout the simulation. The value of V_0 was determined through the application of a chronoamperometric method [84]. The accuracy of an ECM simulation is entirely dependent upon an accurate knowledge base of the behaviour of the important parameters during machining. A more accurate parameter base forms the basis for increased sophistication in the modelling of the ECM process, and in turn can provide an increased knowledge base for tool design methods.

Important ECM parameters include the electrolyte conductivity, the dissolution valency and the overpotential as a function of controllable and easily measurable ECM conditions for example the dissolution current and applied voltage [50, 69, 85]. This chapter outlines how an ultrasound measurement system, developed by D. Clifton at The University of Edinburgh, can be used to allow for the time-resolved measurement of the overpotential during machining. This time-resolved parameterisation for the course of the machining process is achieved through the measurement of the interelectrode gap throughout a machining run.

The experimental work discussed in this chapter was performed by Dr. Rachel Muir.

5.2 Overpotential

As discussed in Chapter 2, the overpotential is the potential required to initialise the migration of ions from the workpiece into the electrolyte solution. Due to the nature of the process, characterisation of electrochemical dissolution current-voltage characteristics at high current densities is experimentally challenging. A previous approach to these problems was proposed by Lohrengel *et al.* [86] for electrochemical micro machining. This approach investigated the machining of Fe in NaNO_3 and NaCl using a novel, flow-through micro-cell with a double-barrelled capillary. These experiments analysed cell voltages and dissolution products on a micro scale, with this information being used to investigate the fundamental

dissolution characteristics of the workpiece. Lohrengel's system benefited from the inclusion of a reference electrode in the cell that allowed absolute voltages to be measured at the workpiece (the anode), this is in comparison to other systems which only provide voltage measurements with reference to the tooling electrode.

However, several disadvantages preclude the use of Lohrengel's micro system for the study of fundamental electrochemical dissolution on macro-electrodes at high current densities. Firstly, the use of the counter electrode results in the generation of additional dissolution by-products, such as hydrogen. As this electrode is situated at the inlet of the flow path, these products are transported through the cell and across the workpiece surface where they can affect the dissolution process. Secondly, there is a relatively complex flow path with the flow impacting perpendicularly against the anode resulting in a less than homogeneous flow path. Finally, this technique does not allow the tool to be fed towards the workpiece and hence equilibrium machining, a potential requirement in industrial ECM applications, is unattainable.

An alternative approach has been suggested previously that has presented details of an ultrasound measurement technique that potentially avoids these problems [87, 88]. This first part of this chapter will present details of the ultrasound method and assesses the feasibility of this ultrasound approach for the measurement of the interelectrode gap and the parameterisation of the ECM process by presenting data recorded across the entirety of the machining run. The results obtained using this new technique will be presented and compared against the established chronoamperometric method. The second part looks in more detail at the behaviour of the overpotential during machining by analysing the results of the ECM of a Jethete workpiece. This will lead onto the work presented in Chapter 6, which introduces the parameterised overpotential model into a time-dependent ECM simulation, and assess the impact on accuracy.

5.3 Ultrasound ECM Set-up

The system used for this investigation consists of a planar workpiece moving at a constant feed rate towards a stationary tool of the same area. The tool used is

divided into seven separate co-planar electrodes (or segments) with narrow insulation separating them (Figure 57).

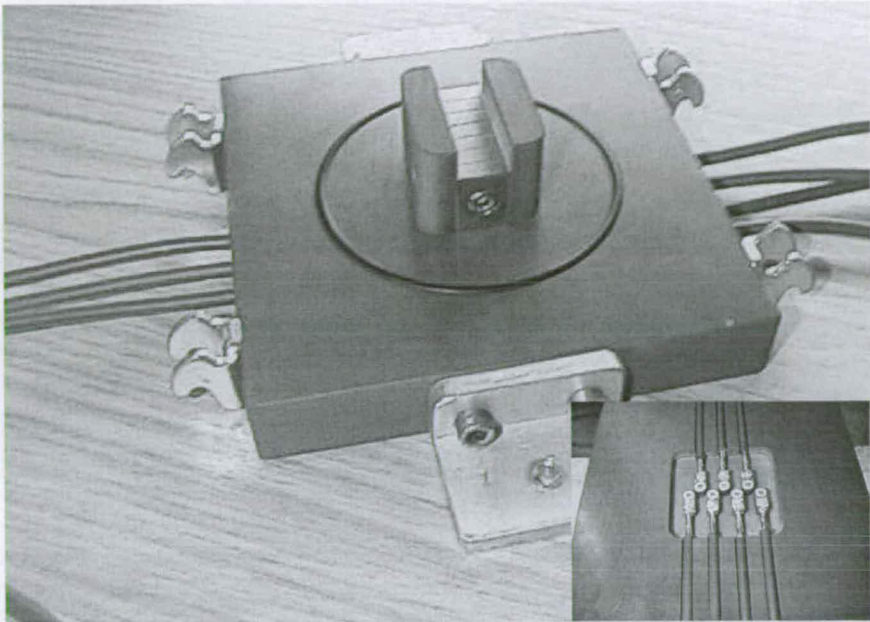


Figure 57: Image of segmented tool, inset is of underside view of segment connections.

The cell, fabricated in house, consisted of a planar workpiece and a parallel, segmented, copper chrome (Columbia Metals Ltd.) tool. The segmented tool comprised of seven segments of equal area, each independently powered and monitored. Segment 1 was located at the flow inlet and segment 7 at the flow outlet (Figure 58). Each of the segments was insulated from its neighbours by 0.05mm mica spacer plates. Since the mica spacer plates are small relative to typical machining gaps the field lines can be considered essentially parallel [89]. Power was fed to each segment individually and the current flow in each segment measured using seven Hall effect transducers.

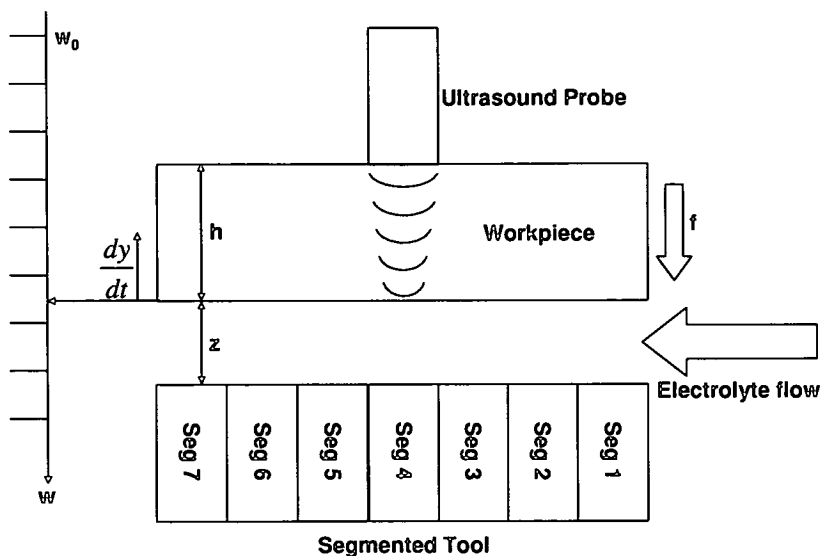


Figure 58: Schematic diagram of the ECM system with the ultrasound probe.

The workpiece was orientated above the tool and approached the tool at a constant feed rate. Both the tool and workpiece were of 40mm length and 15mm width providing an overall area of $A=600\text{mm}^2$. The electrolyte was pumped around the system by a Hydracell model D-25 (Wanner Engineering Inc. USA) three phase continuous pump capable of flow pressures up to 70 Bar and flow rates of up to 45 l min^{-1} . PC Data Logging was carried out using a program written using Visual Designer software (Burr-Brown Inc.). This programme is capable of computing the system parameters in real time during the experiment. The parameters recorded are the overall and segment current transients, the feed rate, electrolyte flow rate and applied voltage.

An ultrasound transmit/receive transducer (Buehler Krautkramer Ltd) was located against the upper face of the workpiece above segment 4 [87] so that the lower face of the workpiece was perpendicular to the probe and orthogonal to the acoustic axis of the ultrasound beam. To maintain a good contact the transducer was sprung loaded. This ultrasound device takes thickness readings of the workpiece throughout the ECM process using the USPC2100 system (Buehler Krautkramer Ltd). This system was run on a secondary PC, with the voltage output relating to the workpiece thickness logged onto the primary PC using the in house software discussed above.

5.4 Ultrasound Measurement Theory

For this analysis it is assumed that the current is governed by migration and also that the flow rate is sufficiently high to remove any soluble and insoluble products from the inter-electrode gap allowing constant electrolyte conductivity to be assumed throughout the experiment. If these assumptions hold, the current across the electrolyte is given by:

$$I = \frac{\kappa(V - V_0)A}{z} . \quad \text{Equation 13}$$

In the ultrasound method, an ultrasound transmit/receive transducer is placed on the top face of the workpiece (Figure 58). This ultrasound probe allows for the measurement of workpiece thickness data, h , throughout a machining run. When this ultrasonic data is combined with a measurement of the position of the tool, w , the time-resolved measurement of the interelectrode gap is calculated using,

$$z = (h_0 - h) - (w - w_0) + z_0 . \quad \text{Equation 14}$$

For means of a comparison between actual and ultrasonic gap measurements, the initial and final gap widths can be measured using a casting agent, thus ensuring the accuracy of this analysis technique. Hence, the ultrasound method provides a time-resolved, non-intrusive gap measuring technique.

Using the recorded z values in conjunction with measured values of applied voltage and current, V_0 can be evaluated using Equation 13, assuming a constant value of κ . The most appropriate current measurement is at the point of the workpiece where the gap is measured i.e. segment 4. This method allows data describing the behaviour of V_0 to be recorded at any point during a machining run without interruption of the process, unlike the established gap measurement approaches.

Further to this, the ultrasound approach also allows time-resolved valency (n) measurements to be made. This is achieved by using,

$$I = -\frac{AnF\rho}{M} \frac{dh}{dt} . \quad \text{Equation 15}$$

In order to reduce experimental noise arising from the measurement of dh/dt , a p point averaged gradient centred at time t over a time interval of $(p-1)\Delta t$, where Δt is a short time period, can be used. This is given by,

$$\left(\frac{dh}{dt}\right)_t = \frac{h\left(t - \frac{(p-1)\Delta t}{2}\right) - h\left(t + \frac{(p-1)\Delta t}{2}\right)}{(p-1)\Delta t} . \quad \text{Equation 16}$$

This equation provides a smoothing of the dh/dt data. The degree of smoothing is determined by the value of p with the observation of real dh/dt changes inhibited over timescales comparable or shorter than $(p-1)\Delta t$.

5.5 Chronoamperometric Theory

The chronoamperometric approach to the analysis of current, voltage and time data from ECM, uses time averaged data to produce a combined parameter for the overall machining process [17].

Mount *et al.* defined the chronoamperometric method for measurement of the overpotential [84]. Equation 17 gives the rate of change in the inter-electrode gap:

$$\frac{dz}{dt} = \frac{k}{z} - f . \quad \text{Equation 17}$$

Using this method, Equation 13, Equation 15 and Equation 17 are combined and differentiated, giving Equation 18 and Equation 19.

$$t = \frac{k}{f^2} \left[\ln \left(\frac{1 - \frac{I_\infty}{I_0}}{1 - \frac{I_\infty}{I}} \right) + \left(\frac{I_\infty}{I_0} - \frac{I_\infty}{I} \right) \right] + t_0 \quad \text{Equation 18}$$

$$t = \frac{k}{f^2} \left[\ln \left(\frac{1 - \frac{z_0}{z_\infty}}{1 - \frac{z}{z_\infty}} \right) + \left(\frac{z_0}{z_\infty} - \frac{z}{z_\infty} \right) \right] + t_0 \quad \text{Equation 19}$$

Equation 18 is used to fit current giving values for k/f^2 for portions of data, using the approximation that k/f^2 in a small fit region is constant.

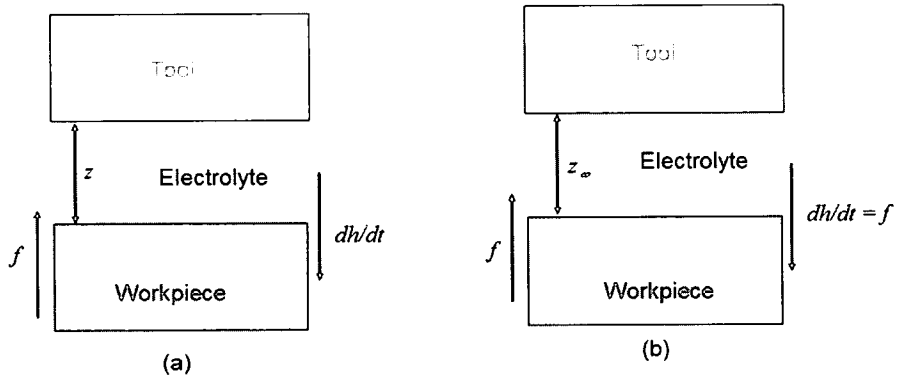


Figure 59: Schematic of planar tool and workpiece set-up (a) before steady state current, equilibrium (b) at steady state current. Relative movement of electrodes is shown by arrows and distance between electrodes by double-headed arrows

Equation 13 relates I and z and can be substituted into Equation 18 to give Equation 19. I_∞ is defined and measured as the constant value of I observed at long t when the dissolution rate equals the feed rate (the equilibrium current, Figure 59) and portions of data are fitted from a defined I_0 , t_0 to I , t . As f^2 is known the k value calculated gives values for V_0 using:

$$k = \frac{\kappa(V - V_0)M}{nF\rho} \quad \text{Equation 20}$$

This method assumes a constant k and hence a constant value of κ , which can generally be assumed at high electrolyte flow [84, 90], and constant value of n , typically calculated at I_∞ , using

$$I_\infty = \frac{nAFf\rho}{M} \quad \text{Equation 21}$$

This is often a reasonable assumption, but changes in n can occur during ECM, particularly through changes in current efficiency due to significant competing anodic reactions at the workpiece such as oxygen evolution [91]. This method gives discrete, mean values for V_0 at intervals along the current transient.

As Equation 18 and Equation 19 are essentially the same equation, if the assumptions discussed hold, both current and gap analysis will yield identical values for V_0 .

5.6 Comparing the Ultrasound and Chronoamperometric Methods

In order to assess the applicability of the ultrasound technique this section compares the two methods outlined previously. Machining took place with the feed rate initially kept constant at $f = 0.5 \text{ mm min}^{-1}$ until equilibrium was reached (the approach phase), the feed was then halted ($f = 0.0 \text{ mm min}^{-1}$), resulting in an increasing interelectrode gap (the retract phase). Additional experimental parameters were established as $z_0 = 1.00 \text{ mm}$ and $V = 8.0 \text{ V}$. The electrolyte used was a 15.0% w/v solution of sodium chloride pumped with a flow rate of $16.0 \text{ litres min}^{-1}$ and was recycled during the experiment from a reservoir with a volume of 60 litres. The conductivity of this electrolyte was measured at $\kappa = 0.20 \pm 0.1 \text{ S cm}^{-1}$, consistent with previous studies [84, 90].

5.6.1 Ultrasound Results

Figure 60 shows a time-resolved plot of the interelectrode-machining gap, z , calculated using Equation 14. As expected z decreases until a steady state machining gap is established during the approach phase. Once the feed is set to zero, z steadily increases, again as expected.

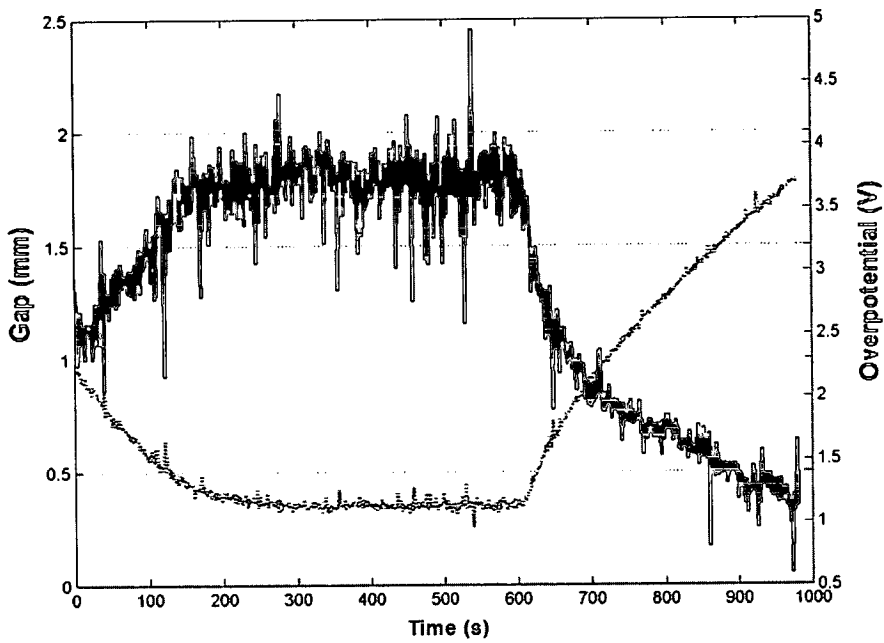


Figure 60: Typical time-resolved plot of the variation in interelectrode machining gap (ooo) and overpotential (==) against time during ECM.

Figure 61 shows the behaviour of the dissolution valency throughout the course of the machining run. The data points have been calculated using Equation 15. Two plots are shown, one with $p=11$, and $p=50$ (Equation 16). This serves to highlight the effect the choice of p has on the calculated valency data. As expected, Figure 61 shows that use of a greater value of p results in a reduction of the noise in our data set. However, the use of such large values of p precludes the measurement of excursions in n over short time periods, and so should be avoided in cases where these would be expected. Reassuringly the data presented is consistent with previous observations for this material [90] with a valency averaged over time of $n = 2.1 \pm 0.1$.

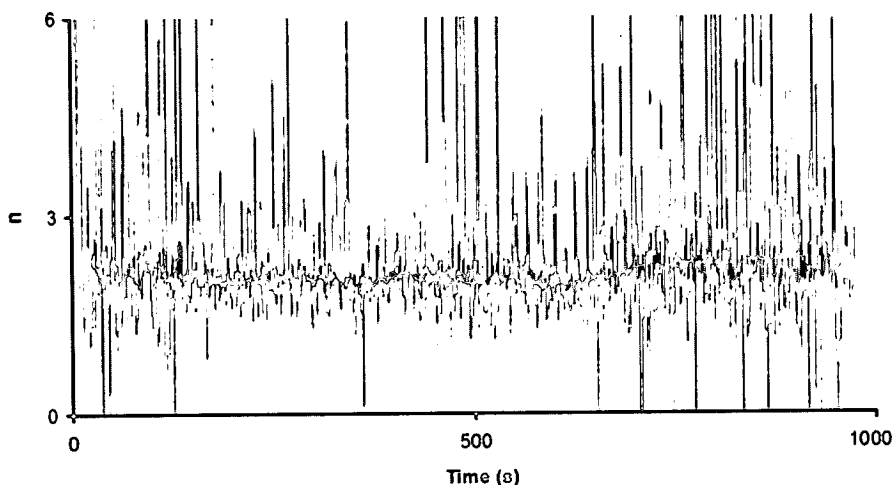


Figure 61: Plots of variation in n against t , $p = 11$ shown in grey and $p = 50$ shown in black.

Using the z data in conjunction with time-resolved V and I data, V_0 has been determined for this experiment using Equation 13. The results of this procedure are also shown in Figure 62. It is immediately apparent that there is a significant variation of V_0 during the machining process. Initially the overpotential increases during the approach phase as I increases, this trend then alters as machining is taking place in the retract phase of the experiment with V_0 decreasing as I decreases. This variation of V_0 with I contradicts one of the assumptions of the chronoamperometric approach, which assumes that there is a relative invariance of V_0 with I . A breakdown of this assumption could result in errors in the parameterisation of the process. In order to provide a comparison of V_0 data, chronoamperometric analysis has been applied to the data set and the results compared with the ultrasound method.

5.6.2 Chronoamperometric Results

Using ECM chronoamperometric theory, with $n = 2.14$ (Equation 21), iterative fitting of Equation 18 to I - t data with $I_{\infty} = 21.15$ and of Equation 19 to z - t data with $z_{\infty} = 0.32$ mm was carried out during the entire approach phase. From these data an average value of k/f^2 was calculated and subsequently average V_0 values were determined (Equation 20). The results of this for both I - and z - analysis are $V_0 = 0.86 \pm 0.42$ V and $V_0 = 2.74 \pm 1.31$ V respectively.

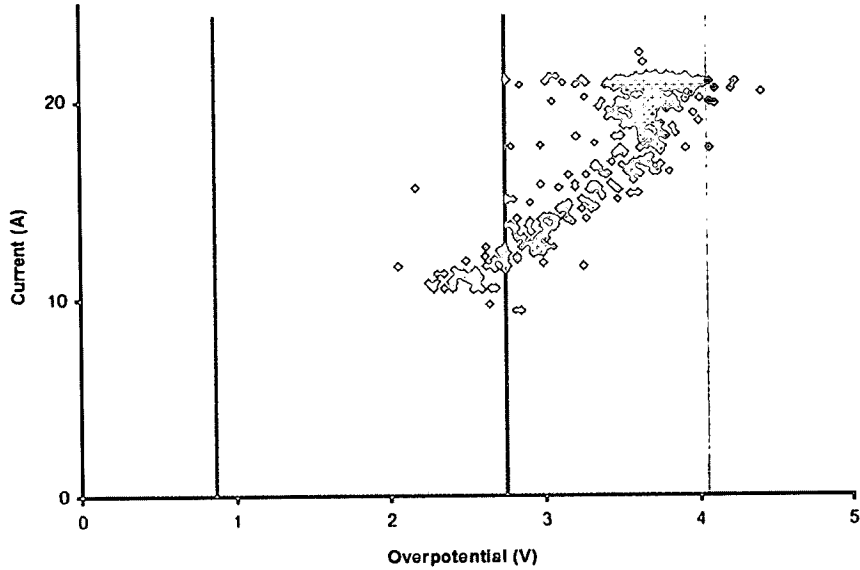


Figure 62: Comparison of time-resolved ultrasound I - V_0 data and global I -analysis, z -analysis data (shaded regions).

When comparing these average V_0 values with those obtained by ultrasound (Figure 62) the V_0 value calculated using z -analysis can be seen to be the most accurate; however it is not surprising given the variation in V_0 with I , which violates the assumption of constant k for this analysis, that the error bar spans the entire ultrasound data set. The V_0 value calculated using the I -analysis is clearly systematically below the entire ultrasound dataset. These large errors can be attributed to the breakdown of the assumptions of constant V_0 and n (through changes in current efficiency and/or oxidation state of workpiece metal dissolution) and the inherent inaccuracy of the iterative curve fitting analysis compared to the

simple linear relationship given by Equation 13. Such large errors are unacceptable for the accurate parameterisation of ECM.

5.6.3 Detailed Chronoamperometric Analysis

To assess whether more accurate I - and z - analysis could be performed over shorter time periods and current ranges, where the assumption of constant V_0 and n is more likely to be appropriate, the data was split into 38 second (40 point) sections and I - and z -analysis carried out on each section during the approach phase. For the I -analysis it was possible to fit 14 sections, while for the z -analysis it was only possible to fit 9. Figure 63 shows the average V_0 values for both I - and z - analysis, plotted at the central I - t value of each section, compared again with the I - V_0 data from the ultrasound method. I -analysis gave V_0 values that showed systematic variation from the ultrasound V_0 data, with large error bars, whilst z -analysis gave V_0 values with much smaller error bars and reassuringly produced values broadly comparable with the ultrasound V_0 data. However, although the values obtained by z -analysis were comparable, the larger errors and the inherently poorer time resolution (which results from both the requirement for multiple data points and the complexity of and hence time for analysis) still make this method markedly inferior to the ultrasound analysis technique.

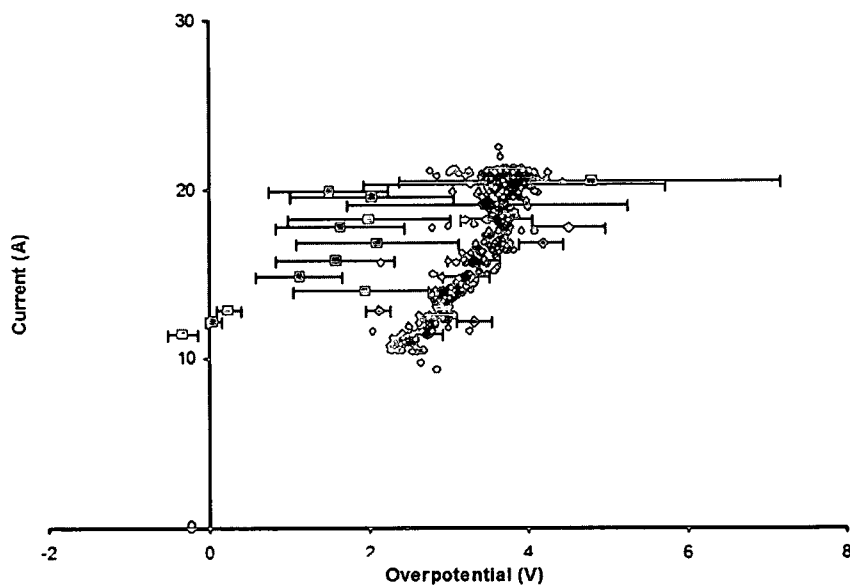


Figure 63: Comparison of time-resolved I - V_0 data and detailed I ($\square$) and z -analysis ($\diamond$).

This superiority of the ultrasound technique for V_0 calculations is not unexpected. The V_0 calculation from the ultrasound technique and (Equation 13) is obtained by combining independent measurements of I and z and contains no valency term. Hence, these measurements are insensitive to changes in n during machining (which are often observed, due to changes in current efficiency [91]). In addition, the chronoamperometric analysis method computes V_0 from k through Equation 20. This calculation requires time averaging as well as an average valency term determined under equilibrium machining which even when valency is constant generally has an associated error of measurement of ± 0.1 . By removing this valency term from the calculations, the errors are therefore significantly reduced. The ultrasound data demonstrate that this decreased error enables sufficiently accurate data to be obtained for the investigation of trends in the I - V_0 data under ECM conditions.

5.7 Investigating the Trends in Overpotential during ECM

Following on from the work shown previously, this section takes a more detailed look at the behaviour of V_0 during machining. To achieve this, results will be presented for the ECM of the alloy Jethete.

5.7.1 Experimental details

The experiment presented here adopted an ‘approach, retract, re-approach’ methodology. Initially z_0 was fixed at 1 mm. Accurate z_0 and z_{∞} measurements were confirmed through casting using a polyether impression material (EPSE Permadyne) [89] to three decimal places. Using this technique the workpiece was initially machined to an equilibrium state using $f=0.5 \text{ mm min}^{-1}$ (the approach phase). The feed was then halted, $f = 0.0 \text{ mm min}^{-1}$, resulting in a recession of the workpiece surface (the retract phase). Once equilibrium had been reached for a second time, the feed was re-applied at $f = 0.5 \text{ mm min}^{-1}$, and the workpiece again was machined to an equilibrium (the re-approach stage). Throughout machining $V = 15.0$ volts and unless otherwise stated the electrolyte used was a 12.0 % w/v solution of sodium chloride, the electrolyte temperature was maintained at 30°C by use of a cooling coil and $U = 16.0 \text{ litres min}^{-1}$. κ was measured and considered constant due to the high value of U [84]. For purposes of discussion a second experiment was performed using variation in the experimental parameters of z_0 fixed at 3 mm and use of a 15.0% w/v solution of sodium chloride electrolyte. The remaining parameters were kept the same.

In order to remove any compositional variation, the workpieces were subjected to heat-treating prior to use according to the manufacturer’s (Bodycote International Plc.) annealing process. This heating process involved heating the workpiece in air at 990°C for 18 mins, then 670°C for 36 mins and at 655°C for 36 mins.

5.7.2 Results

Figure 64 shows both typical current transients when machining J and the interelectrode gap measurements. Measurements of z_0 and w_0 were made prior to machining and the time-resolved gap measurements are calculated using Equation 14.

Figure 64 clearly demonstrates the approach phase, where an equilibrium gap is established ($z_{\infty} = 0.79 \pm 0.02$ mm), followed by the retract phase, where z increases with time as dissolution occurs, and finally the re-approach phase. The final gap measurements determined by ultrasound and casting were found to be equal, demonstrating the accuracy of this ultrasound gap measurement method. The variations in segmented currents arising from the rounding effects discussed previously can also be observed, with segment 1 and 7 producing lower readings during the re-approach phase of machining.

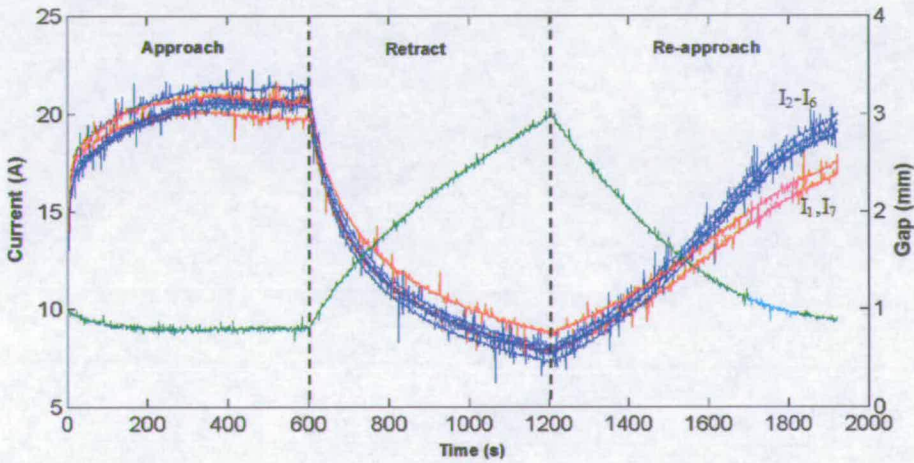


Figure 64: Typical current transients for segments 1-7. The current observed for each segments 1 to 7 are indicated and marked I_1 to I_7 (—); the time dependent behaviour of the end segment currents I_1 and I_7 are similar, but different from I_2 to I_6 (—). The approach, retract and re-approach phases are indicated in this and subsequent plots for clarity. Also shown is the z -time data (—) derived from the ultrasound measurements.

Figure 65 shows the results of the valency analysis for $p=11$ and $p=50$ giving an average $n = 2.3 \pm 0.5$ and $n = 2.3 \pm 0.3$ respectively.

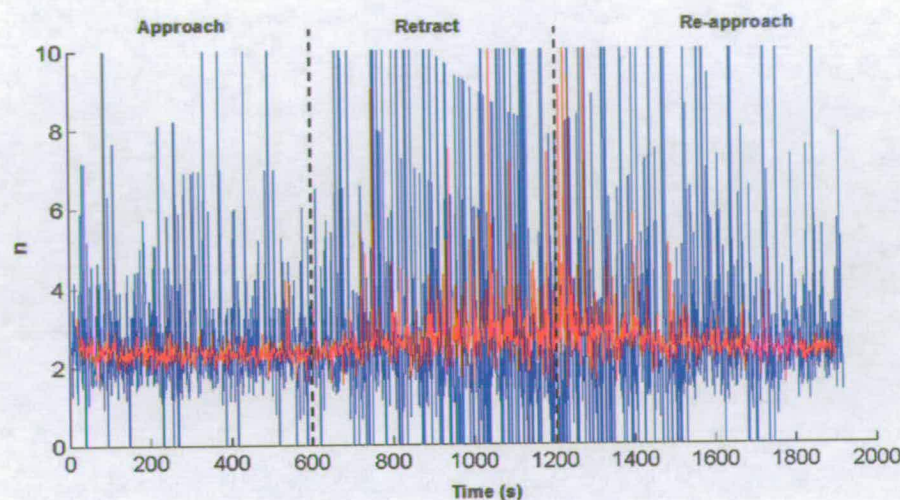


Figure 65: The corresponding calculated time-resolved n data for $p=11$ (—) and $p=50$ (—) for the experiment in Figure 8.

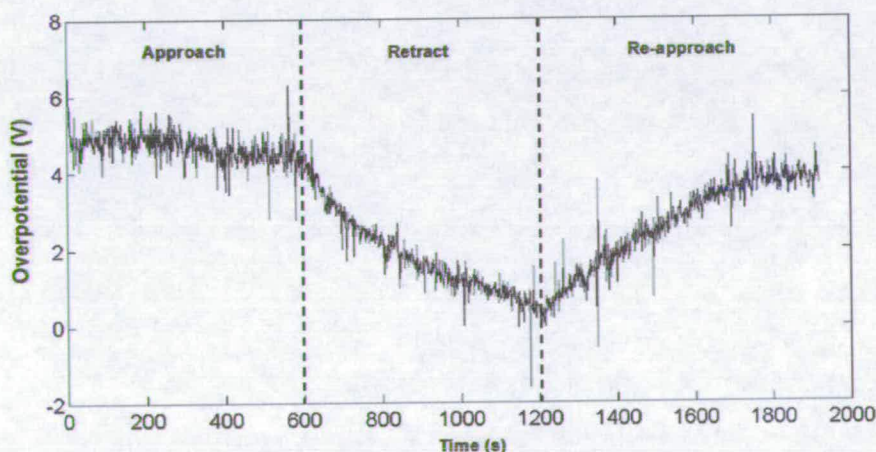


Figure 66 shows the time-resolved values of V_0 throughout machining. These values have been determined at segment 4 (the segment where the ultrasound probe is situated) using Equation 22 [88]:

$$V_0 = V - \frac{Iz}{\kappa A} \quad \text{Equation 22}$$

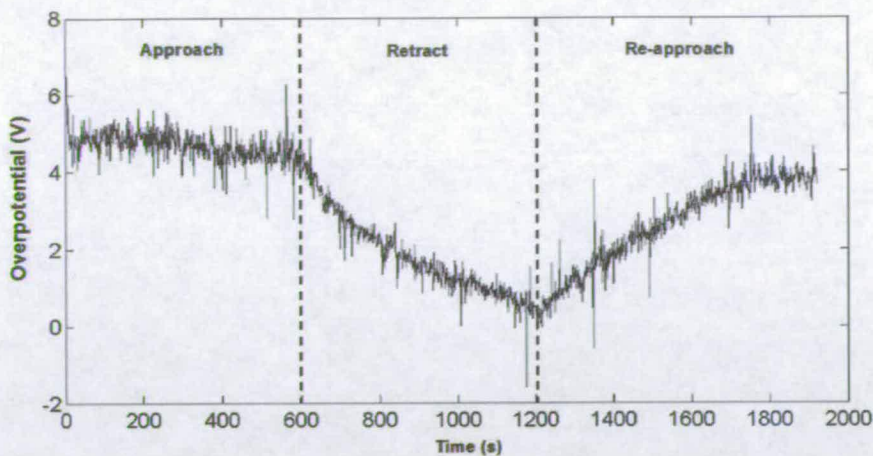


Figure 66: The corresponding V_0 data for the experiment in Figure 64 as a function of time

Figure 67 displays the behaviour of $I-V_0$ during the approach, retract and re-approach stages of machining for a single experiment.

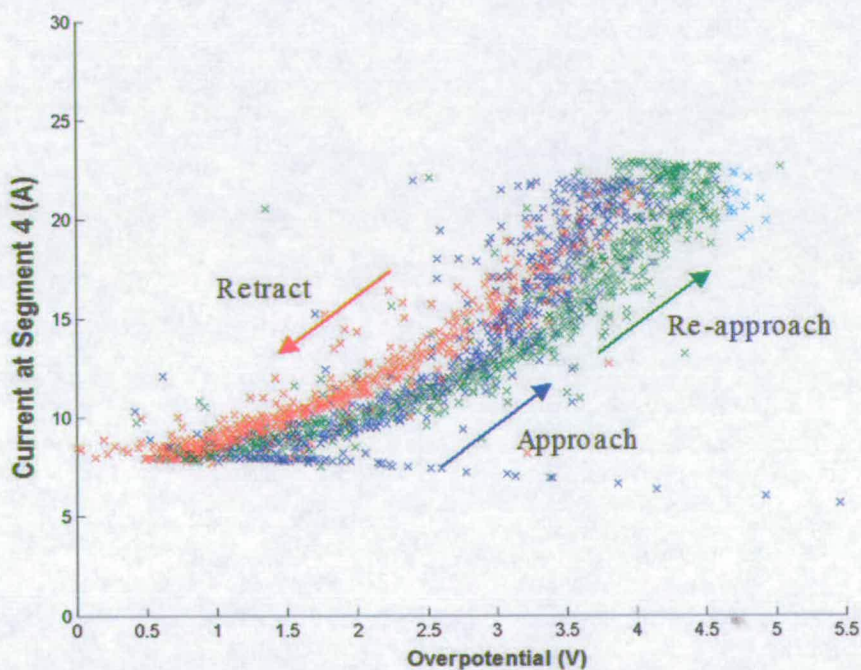


Figure 67: Approach ($\times\times\times$), retract ($\times\times\times$) and re-approach ($\times\times\times$) $I-V_0$ data for the $z_0 = 2.960$ mm data.

5.7.3 Trends in I vs. V_0 data

The main trend present in I - V_0 results (Figure 67) is a positive linear dependence of I on V_0 . This can be attributed to a passive layer that is formed on the surface of the workpiece during ECM [32, 33]. There is some debate as to the composition of this film, though for computational simulation purposes, the actual composition of this layer is not as important as the ability to identify and highlight the effects induced by its presence.

The migrational transport across the surface film is expected to be an ohmic process, with a linear dependence of I on V_0 for a constant film resistance. The positive, near-linear, dependence of I on V_0 during machining indicates that this ionic transportation through this film is the rate-determining step of metal dissolution during ECM. The average resistance of the surface film can be estimated from the average gradient of the I - V_0 data in this dissolution current range (10-25 A cm⁻²). This is of the order of 0.2 Ω cm², a markedly lower resistance than previous work measuring film resistances. Studies using current densities of the order of 0.1 A cm⁻² to induce dissolution of iron microelectrodes [86] have calculated resistances of 1-2 Ω cm² when performing cyclic voltammetry. Higher film resistances (200-300 Ω cm²) have been found from cyclic voltammetry for the steel 304L in 0.1 M NaOH [92] under ambient conditions using very low applied voltages and current densities. This variation provides a strong justification for performing parametric measurements under the ECM conditions of V_0 and I to ensure their applicability to the process. These results show that a decrease in film resistance is observed for the higher dissolution currents of ECM. This can be attributed to an increase in the film ionic conductance arising from either an increase in vacancy concentration and/or film thinning due to the higher surface driving voltages.

Additionally it is highly satisfactory that, the I - V_0 data for both $z_0 = 1.055$ mm at 12% w/v NaCl and $z_0 = 2.960$ mm at 15% w/v NaCl gaps follow an essentially common curve (Figure 68). This implies that the I - V_0 curve is independent of ECM conditions such as electrolyte conductivity and initial gap.

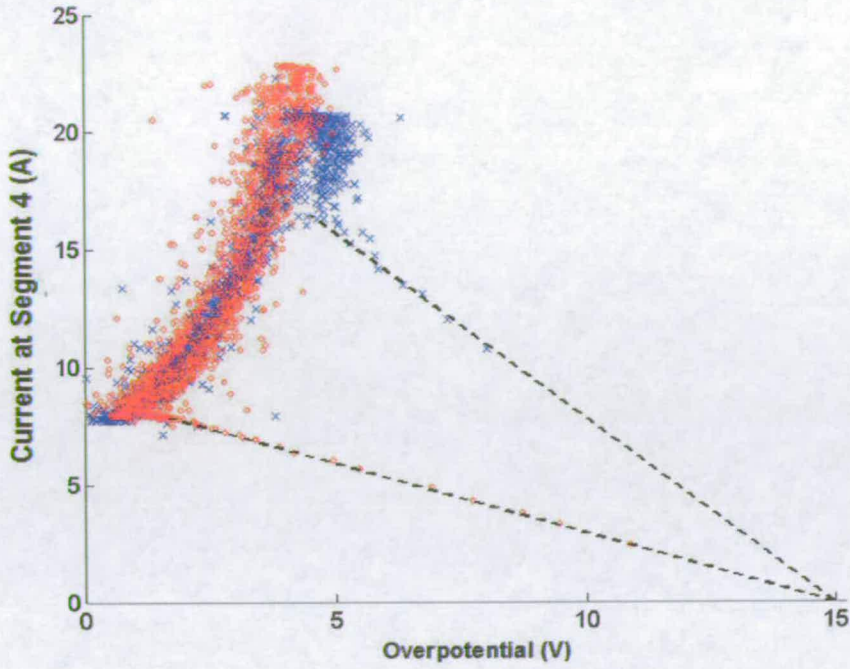


Figure 68: Typical $I-V_0$ data for the electrochemical dissolution of J with $z_0 = 1.055$ mm and an electrolyte concentration of 12% (xxx), and $z_0 = 2.960$ mm and an electrolyte concentration of 15% (xxx). Also shown are theoretical lines calculated from Equation 22 with the appropriate electrolyte conductivities of $\kappa = 0.184 \text{ S cm}^{-1}$ and $\kappa = 0.210 \text{ S cm}^{-1}$ respectively.

There is a slight exception for the $z_0 = 1.055$ mm approach phase which produces initially higher values of V_0 that can be attributed to the temporal mixing of two V_0 effects, one of which is the characteristic behaviour during ECM, the other is an effect that arises at the start of machining. Initially, for the first 7 seconds of machining, a linear decrease of V_0 with I is observed. Equation 22 can be differentiated with respect to the two variables during machining, V_0 and z , to give

$$dI = -\frac{\kappa A}{z} dV_0 - \frac{\kappa A(V - V_0)}{z^2} dz. \quad \text{Equation 23}$$

Initially $(V-V_0)$ is small and z is large and therefore the second term of Equation 23 can be assumed to be negligible. Thus, Equation 23 simplifies to:

$$dI = -\frac{\kappa A}{z} dV_0 \quad \text{Equation 24}$$

Equation 24 suggests that V_0 would initially be expected to show a linear dependence on I with a gradient of $-\kappa A/z$. This can clearly be seen in the close correspondence of the approach transients of two experiments with $z_0 = 1.055$ mm and 2.960 mm (Figure 68) with the lines corresponding to the theoretical values $-\kappa A/z$ for each experiment. As machining commences, V_0 is large and comparable to V , however V_0 rapidly decreases towards values characteristic of ECM. This indicates that initially in order to start ion migration through the passive layer, establishing the conditions for workpiece electrochemical dissolution, V is applied essentially entirely across the surface film. As the electrodes approach and the onset of machining, the second term in Equation 23 begins to dominate and there is a positive dependence between V_0 and I .

Figure 68 also demonstrates that in the experiment where electrochemical dissolution is initiated at lower I values, the gradient of $I-V_0$ can be observed to increase during the approach phase. This is indicative of an overall reduction in the film thickness over time resulting in a decrease in passive film resistance since a constant gradient would only be expected if migration of a fixed number of ions across a film of fixed thickness were occurring, driven by V_0 .

Finally, it is clear from Figure 67 that there are relatively small but significant differences in $I-V_0$ behaviour when closely comparing the approach and retract stages. V_0 can be seen to decrease with time during equilibrium machining at high currents at the end of the approach phase (Figure 66) which results in lower V_0 values as the electrodes are retracted. The annealing of the workpiece prior to ECM ensures compositional homogeneity and precludes the possibility of this being due to compositional variation within the workpiece. A possible explanation for this is that the passive film layer is degrading due to the high ionic transfer

rates. At lower currents, the film is able to repair, resulting in the re-approach curve being comparable to the approach phase.

5.8 Conclusions

The results presented in Section 5.6 indicate that a variation in V_0 occurs throughout machining. These results have subsequently been compared to results obtained using the previous chronoamperometric method. It has been shown the accuracy of the ultrasound analysis method exceeds that of the chronoamperometric approach and the ability to collect continuous accurate V_0 and z data without disrupting the machining process (as with alternative techniques), demonstrates the power of this approach in the parameterisation of ECM.

Section 5.7 demonstrated the use of this ultrasound technique though the analysis of the current-voltage bulk dissolution characteristics of Jethete. These have been measured under the high flow, high feed rate conditions applicable to industrial ECM. This work highlighted some of the variations in the overpotential that occur during prolonged dissolution through a surface film. The results show that the I - V_0 relationship was not affected by starting gap or conductivity, showing that it is a property that is characteristic of the workpiece material.

The overpotential behaviour presented and discussed will allow the accommodation of I - V_0 trends present during ECM as a more refined, parameterised model into the ECM simulation presented previously.

Chapter:

6 Developing a Non-Ideal ECM Simulation

Part B: Developing a Time-Dependent Simulation of ECM under Non-Ideal Conditions

Following on from the experimental work in the previous chapter, this chapter forms the second part of the overpotential analysis by introducing a parameterised model into a time-dependent simulation. The methodology required to integrate this model is outlined, followed by an analysis of the benefit of its inclusion through comparison with experimental results. Finally the implementation of this model into non-flat workpiece profiles is discussed.

6.1 Introduction

This chapter is a continuation from the work presented in the previous chapter (Chapter 5) where it was demonstrated how the characteristic overpotential variations can be measured as a function of the dissolution current. It is believed that with the inclusion of a model based on this characterisation work, a more accurate numerical simulation can be produced. This section of work involves the integration of a variable V_0 parameter into the existing two-dimensional, time-dependent simulation of the ECM process. In order to achieve this, the linear relationship between I and V_0 is integrated with the existing numerical algorithms used in the simulation.

The work discussed here has previously presented in a conference paper presented at Electrocor 2005, Cadiz by the author.

6.2 Integrating a parametric overpotential model

The non-intrusive, ultrasound technique presented previously allowed for the real-time measurement of the inter-electrode gap, and subsequently calculation of the overpotential variations during machining. Additional monitoring of the current transients during machining allowed V_0 to be plotted as a function of I . Figure 69 shows a typical I - V_0 plot for data collected using this technique. The data shown is from the ultrasound sound system whilst machining a SS410 workpiece was machined with an applied voltage of 8V in a sodium chloride electrolyte.

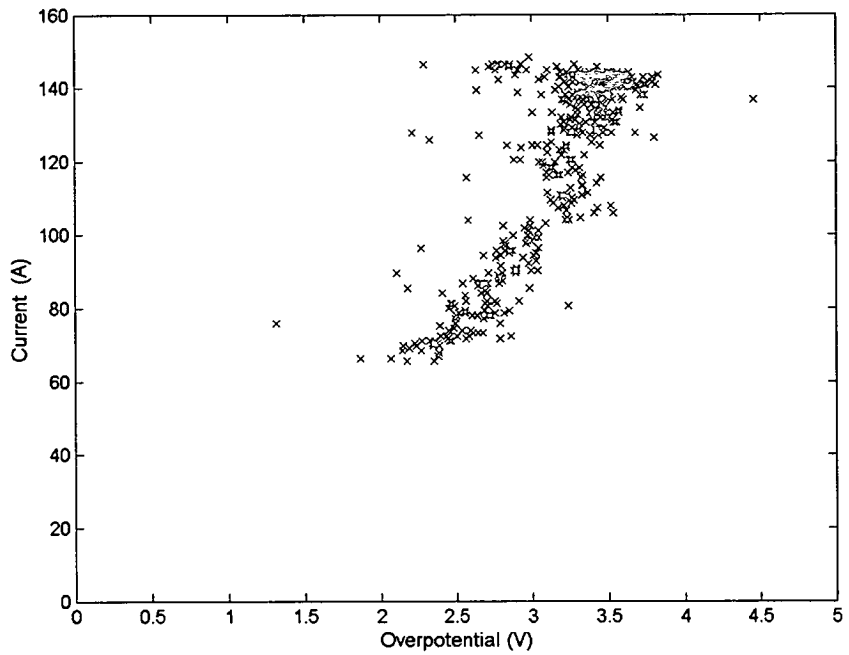


Figure 69: An $I-V_0$ graph for the machining of SS410 at 8 V in NaCl

It is clear that there is an almost linear dependence of the overpotential on the current. The linear nature of this dependence is the result of ionic migration through a passive film that is formed on the surface of the workpiece. Ohm's law states that

$$R = \frac{V}{I} \quad \text{Equation 25}$$

hence the gradient of this straight-line relationship can be given as the resistance of the oxide film.

Due to the linearity of this $I-V_0$ relationship, a straight-line fit, based on a root-mean squared method, can be used to generate a parameterised model that can determine the V_0 based on the current values (Figure 70).

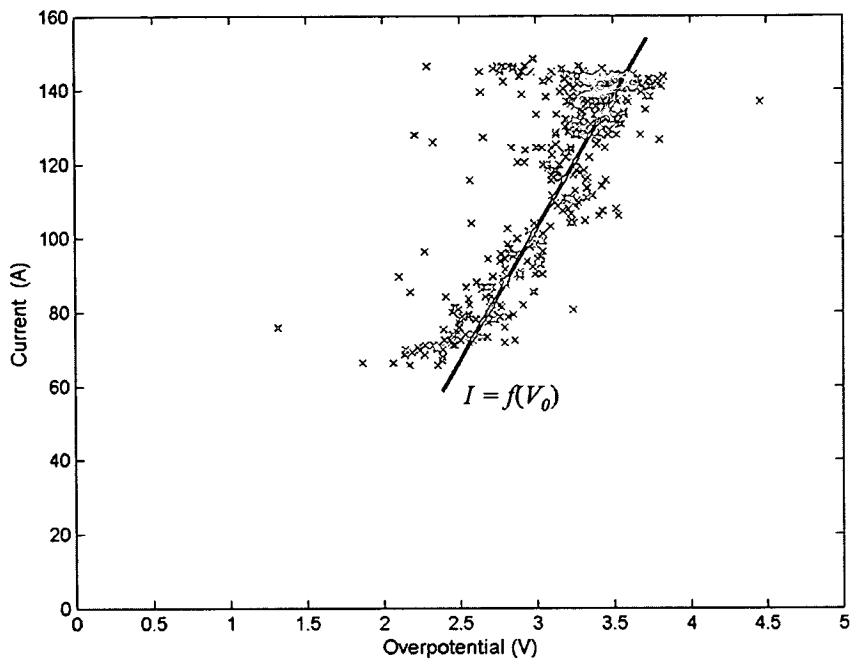


Figure 70: The linear fit through the I - V_0 data

By introducing this model into the simulation structure, the required variations in V_0 as a function of current can be produced. This will allow for a time-dependent variation of the overpotential to be applied throughout the course of machining.

6.3 Modifications required to the simulation

In order to incorporate this parametric model into the simulation, a number of modifications need to be made to the simulation code. The main part of this is required in the processing scripts, though some additional modifications are required to enable to user to input the required parameter model values, and present the variations of the overpotential as a function of machining time and other logged data. The inclusion of this variable V_0 model into processing code required consideration of the following items:

- Input of required model parameters
- Translation of $I-V_0$ relationship to $J-V_0$ relationship
- Calculation of initial condition
- Inclusion of a calculation into the iterative solver
 - Including application of V_0 to the tool boundary
- Post-processing capabilities

6.3.1 Input of the required model parameters

The input values required for this non-ideal simulation are the constants A and B that define the slope and the intercept of the $I-V_0$ curve. These constants equate to

$$I = AV_0 + B.$$

The pre-processor code was modified to request that the user inserts these values into the simulation. At this stage these inputs need to be referenced from experimental data using an external data analysis tool to perform the line fit. Further development of this code would allow these characteristic values to be associated with a specific material type, and thus only a single input from the user would define the model to be used.

6.3.2 Translation of I - V_0 relationship to J - V_0 relationship

The input parameters, A and B , are defined based on experimental data that describes the I - V_0 relationship. For use in the simulation this linear model needs to be converted into a J - V_0 relationship, since the processing script extracts values for J following the solution of the Laplace equation. Through integration the current for the workpiece as a whole can be obtained, I cannot be defined as a function of length in the form of current density. For the case of a flat-tool machining a flat workpiece, the I - V_0 relationship holds true since the inter-electrode gap remains constant along the flow path, though it fails for any other case where the gap varies.

The conversion is a simple one and uses the input of the length ($l = 0.04$ m) and width ($w = 0.015$ m) of the planar workpieces discussed in Chapter 5. The relationship between J and I is defined as,

$$J = \frac{I}{lw} . \quad \text{Equation 26}$$

Consequently which means the J - V_0 relationship is defined as,

$$J = A_J V_0 - B_J , \quad \text{Equation 27}$$

where,

$$A_J = \frac{A}{lw} \quad \text{and} \quad B_J = \frac{B}{lw} . \quad \text{Equation 28a and 28b}$$

These conversions are calculated in the pre-processor following the input of the A and B variables by the user.

6.3.3 Calculation of initial V_0 condition

The ideal simulation requested the V_0 value to be inputted, and subsequently assigned to the boundary segments forming the tool boundary, at the pre-processing stage of the simulation. This value remained constant throughout the duration of the simulation. Since there is now no V_0 input in the pre-processor, the initial condition needs to be calculated to prevent failure of the FEA. Use of $V_0 = 0$ is possible, the experience of the author is that this can result in an unrealistic deviation in material removal rates during the first time step that can take a number of time-steps to resolve. This is especially prevalent as in actual machining there is an initial period where the overpotential is very high as the process of ion migration begins. One solution is to run with smaller time-step size, though this will increase simulation time, the other is to use a non-zero starting V_0 . It is the second option that has been chosen, and allows the user to choose a suitable starting value based on the characteristic curve and anticipated starting conditions. Observation of the current transient through the early time-steps will determine whether a suitable starting value has been chosen⁴.

6.3.4 Inclusion of time-dependent variation calculation into the iterative solver

With the pre-processing calculations for the inclusion of this model in place, the processing section of the code needs to be modified to allow V_0 to be calculated at each time-step and fed back to the FEA solver through modification of the boundary conditions. For the purposes of this validation work, the assumption is made that the simulation is machining a flat tool with a flat workpiece, hence J can be considered uniform along the length of the flow path. It then follows that although the V_0 used in the simulation varies with time, it will remain a constant boundary condition for each of the workpiece boundary segments during in each iteration of the solver. Section 6.6 of this chapter discusses the methodology required to introduce this parameterised model to the case of a non-flat tool machining an initially flat workpiece.

⁴ A more automated system may incorporate a system of convergence between the pre-processor and the processor, where the initial V_0 value is determined through repeated analysis and observation of the current along the workpiece boundary as it tends to an initial starting value for the machining conditions.

During each iteration, following the solution of the Laplace equation, the current density is extracted along the workpiece. This value is then averaged for the case of the flat workpiece to give a single value for J . Using this J value with

$$J = A_J V_0 - B_J , \quad \text{Equation 27}$$

results in a V_0 value that can be assigned to the next iteration. This value is then used in the calculation of the anode boundary condition ($= V_i - V_0$). The assignment of this value is based on the boundary ID index described in Chapter 3.

Since the V_0 value for each iteration is reliant on the results of the previous iteration, the size of the inputted time step must be considered. If too great a step is taken then the resulting overpotential may not be representative of the behaviour of the actual V_0 during machining.

6.3.5 Post-Processing modifications

The post-processing capabilities of the simulation were also modified so that the calculated V_0 values are logging for the duration of the simulation in the same manner as other calculated parameters (Chapter 3). This enables the transient V_0 values created in the simulation to be plotted against other simulation parameters.

6.4 Validation of the Non-Ideal Simulation

This section demonstrates the effect of using the parameterised overpotential model in the ECM simulation by comparing results against a simulation with a constant V_0 value for duration of the machining run (ideal-simulation conditions) as well as results collected for an actual experimental run.

6.4.1 Experimental Set-up

The machining set-up used is that of a planar tool and workpiece. This allows gap width to be monitored during the simulation via the ultrasound probe. Both the tool and workpiece were 40mm length and 15mm width providing an overall area of $A=600 \text{ mm}^2$. The workpiece material used was titanium 6/4. The experimental set-up is the same as described in Chapter 5.

The initial gap (z_0) was measured to be 0.8 mm. Both initial and final gap measurements were confirmed using the same method. The workpiece was machined to an equilibrium state using $f = 0.5 \text{ mm min}^{-1}$. Throughout machining $V_t = 15$ volts and the electrolyte used was a 12.0 % w/v solution of sodium chloride, the electrolyte temperature was maintained at 30 °C by use of a cooling coil and $U = 16.0 \text{ litres min}^{-1}$. κ was measured to be 20 S m^{-1} and considered constant due to the high value of U .

6.4.2 Simulation Set-up

The simulations were performed on a PC with Dual Pentium 4 3.06GHz processors and 2Gb RAM. In order to ensure that any deviations in the comparisons were a direct result of the parameterised V_0 model, the feed, the valency and the applied voltage were set to experimentally stored values. Figure 71, shows the data measured during the experiment for calibration of the V_0 model.

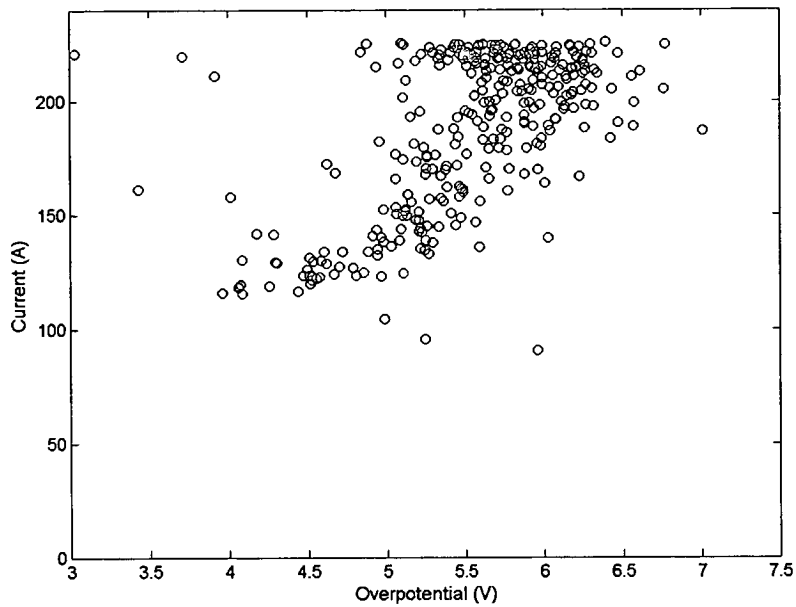


Figure 71: $I-V_0$ plot recorded during machining of actual titanium workpiece

The additional simulation parameters were:

Component	Parameter	Value
Material Properties	Atomic Mass	45.8
	Valency	4
	Density (kg m^{-3})	4418
Experimental Parameters	Starting gap (mm)	0.8
	Electrolyte Conductivity (S m^{-1})	20
Simulation Parameters	Time step (s)	2
	Total Time to Simulate (s)	290

The ideal simulation used the same input parameters except for V_0 , which was set to the mean of the measured experimental V_0 values ($V_0 = 2.88 \text{ V}$).

6.4.3 Results and Discussion

Presented here are the results of the experiment and the simulation runs. Figure 72 shows the $I-V_0$ for the experimental data and the values calculated by the simulation.

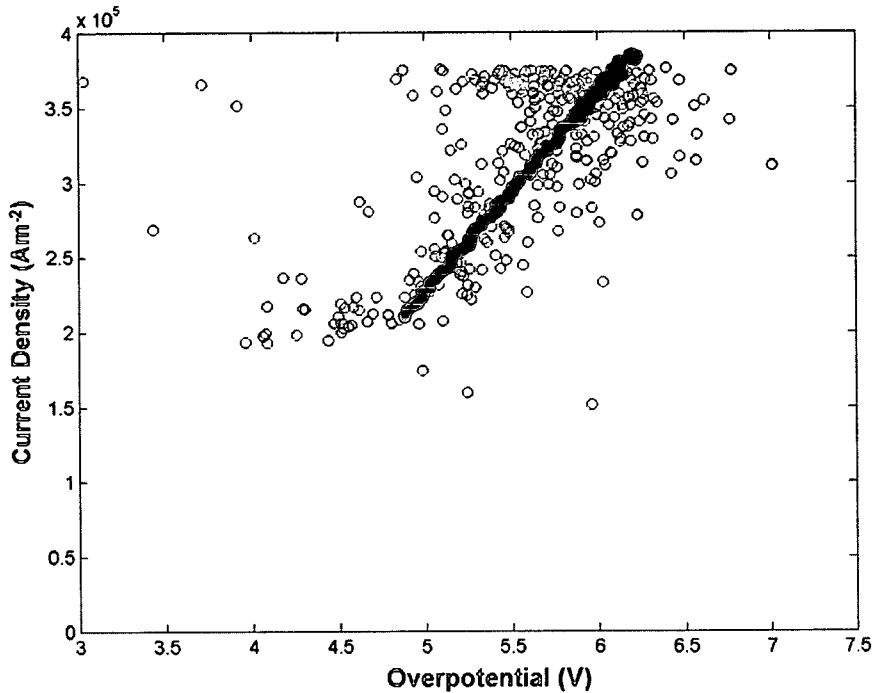


Figure 72: Comparing the $I-V_0$ trend for both experimental (○) and simulation (⊙) data

These results demonstrate that the parameterised model closely follows the straight-line model during the simulation. In addition, it is shown that the currents being calculated during the simulation have a close correlation with the experimental data.

Figure 73 is a comparison of calculated z between a simulation using the constant V_0 and the simulation with the parameterised V_0 model. In addition these results are also compared against data collected experimentally and measured using the ultrasound method.

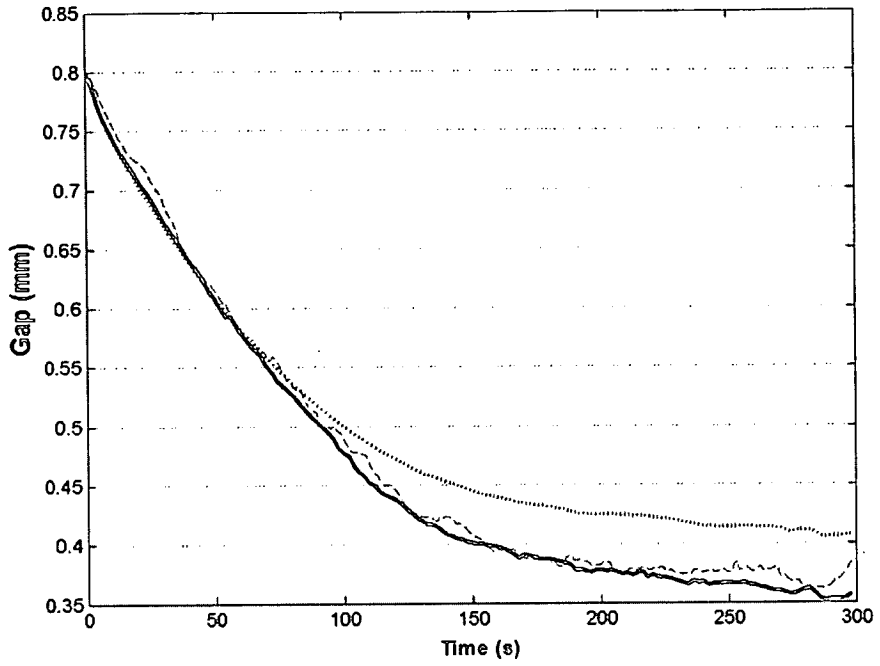


Figure 73: Comparison of z for experimental (---), non-ideal simulation (—) and ideal simulation (···).

The z vs. t graph (Figure 73) shows that the non-ideal simulation closely follows the experimental data throughout machining. The ideal simulation z initially matches the experimental data. After 100 seconds however, it deviates from the experimentally measured z occurs and the gap in the simulation grows wider.

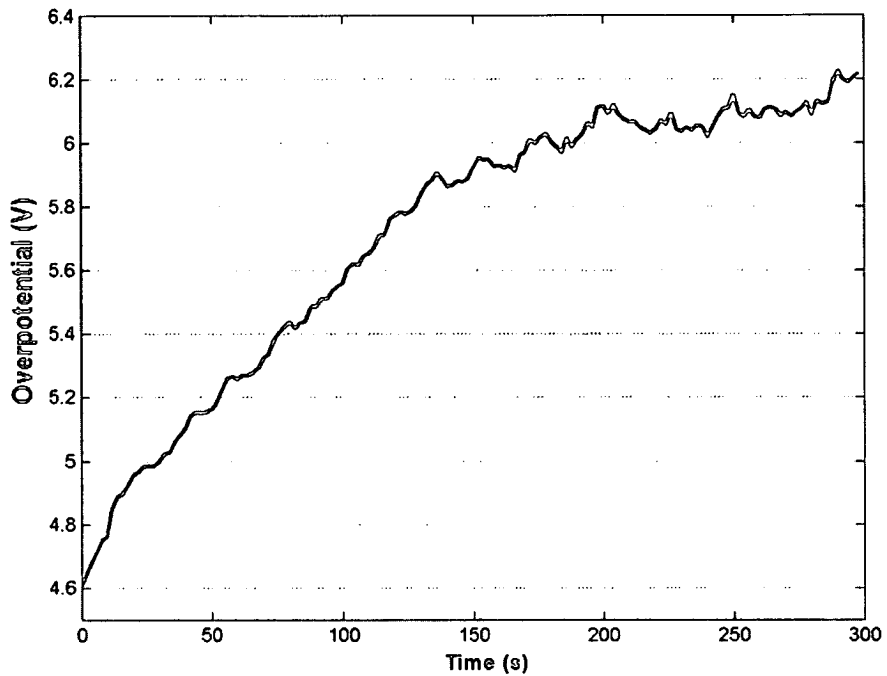


Figure 74: Calculated V_0 plotted against time for the non-ideal simulation

Figure 74 demonstrates that V_0 in the non-ideal simulation rises over the course of machining. This increase results in less material being removed during each time step and consequently, a smaller z as machining progresses. With a constant V_0 the potential difference remains the same throughout machining and consequently more material is removed. Following this logic it would be natural to expect Figure 73 to indicate more material removal in the early stages of the non-ideal simulation than in the ideal simulation, since the potential difference is greater. This would be the case had the tool and the workpiece started with a smaller z_0 . Figure 73 indicates a linear drop in z between 0 and 75 seconds. This is the rate at which the tool and workpiece are being fed together. Not until over 75 seconds does the magnitude of material removal become sufficient for the simulated z -values to show deviation. At the end of machining, the difference in z has been calculated to be 0.05mm.

6.5 Conclusions

So far this chapter has presented the methodology required to implement a parametric overpotential model into a time-dependent simulation of ECM. The results presented show that a significant improvement in material removal and gap calculations is achieved when simulating using this overpotential model. This unique piece of experimentally validated work demonstrates for the first time the impact of including such a characterised model into simulations of the ECM process.

Following on from this the next section discusses how this model can be implemented into simulations that involve a non-flat workpiece profile – a condition applicable to nearly all industrial ECM applications.

6.6 Non-ideal Simulation Using a Non-Flat Tool

The results of this validation study demonstrated the increased accuracy achieved by the inclusion of a parameterised V_0 model in an ECM simulation using a planar tool and workpiece configuration. This set-up is very much an experimental scenario with only a small scope for application in an industrial environment. Only in cases where the assumption of a localised uniform gap width could the method be applied. An example of such a case would be the machining of a workpiece using a flat, universal electrode to locally smooth a workpiece. A more advanced model is required to simulate machining involving non-flat tools and workpieces. This section discusses the additional modifications required to adapt this parameterised overpotential model into a two-dimensional machining scenario.

The use of a flat tool and workpiece profile results in a constant inter-electrode gap along the length of the workpiece. Since the gap is constant, the calculated current density can also be considered constant along the length of the flow path resulting in an overpotential value that remains uniform along the length of the workpiece profile though varies with time. This assumption of a constant gap is in compatible with the case of machining with a non-flat tool or workpiece since the interelectrode gap, and subsequently the current density and overpotential, will vary as a function of the length of the workpiece. Incorporating this variation is the key to producing a working simulation.

6.6.1 Modifications required

The variations of V_0 along the length of the workpiece impact heavily upon the methodology used to describe the boundary conditions for the segments that make up the workpiece profile within the simulation. A constant V_0 value means that each of the boundaries defining our workpiece are assigned the same value. This is simple to implement provided the boundary segments of the workpiece can be identified. The inclusion of a V_0 variation along the workpiece length requires the creation of an individual boundary condition for each workpiece boundary segment based on the J and subsequently V_0 values at, the end points of each of the boundary segments, the workpiece node points (i_N).

If we consider one of our iterations, the implementation of this method requires the following stages:

- Calculation of J and V_0 at each i_N .
- Identification of corresponding boundary ID's based on i_N as start and end points.
- Definition of a suitable boundary condition.

Calculation of J and V_0 at i_N

This is a simple adaptation from the planar example described previously. The algorithm developed from the ideal, non-flat tooled simulation (Chapter 3) required J -values to be stored at each i_N to calculate the material removal at that point during each time-step. Consequently the internal simulation structure exists to produce a value of V_0 at every i_N .

Identifying Boundary ID's based on i_N as start and end points

Each i_N define the start and the end point of one of the boundary sections. In order to integrate the parameterised V_0 model, the identification of which i_N correspond to each boundary section is essential.

Initially the simulation can use the same algorithm as previously, where the solution of the Laplace equation is found, J and dh are calculated, the relocation of i_N and the reforming of the geometry for the next iteration takes place. Once this geometry is created additional tasks and indexes need to be created before the boundary conditions are established. Using the technique discussed in (Chapter 3), the ID numbers of the boundary forming the workpiece are extracted and stored in a new index. Using further geometry analysis tools, it is possible to identify the location of the start and end points in Cartesian space of each of these boundary sections. Since the location of our i_N is known - their co-ordinates calculated during the material removal stage - the simulation can adopt a 'look-up' algorithm that associates the i_N to these boundary end points. Once each boundary has two i_N associated with it, the value of V_0 at start and the end of our boundary section is also known. At this stage boundary ID and the corresponding start and end point V_0

values are stored in a new index to be used in the definition of the boundary conditions.

Defining Suitable Boundary Conditions

With knowledge of the boundary ID's and the start and end conditions, the next stage is to define the functions required to represent the change in V_0 along the boundary length. This is essential to produce a smooth variation of V_0 along the entire workpiece boundary. Simply assigning an average of the start and end values results in a disjointed FEA result at i_N , producing an invalid J data set for material removal⁵. What is required is a boundary definition that uses the start and end V_0 of each of the boundary sections to create a function to define the variation in V_0 along the length of the boundary. In this manner, a unique value of V_0 at each i_N is maintained.

The system proposed defines the variation along each boundary section (Γ) as a linear function based on the V_0 values at the start and end points. Consider the case of a single boundary.

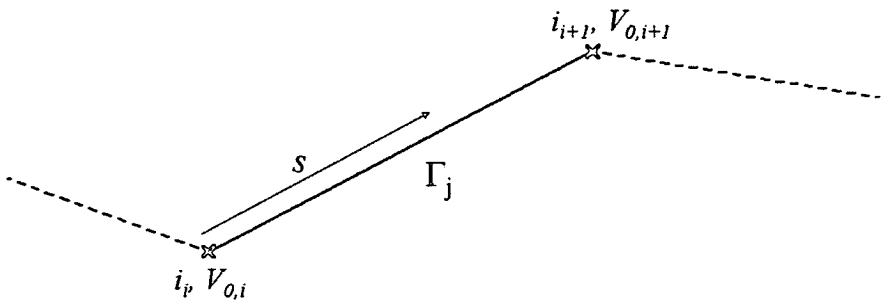


Figure 75: A single boundary segment in the ECM simulation

Each of the boundary sections is a straight line geometry object, and since the lengths of these sections may vary slightly, a parameter s that varies from 0 to 1 over the length of the boundary is used to determine the rate at which V_0 varies

⁵ Since the FEA solution is based on the boundary conditions and the J data export is based on i_N locations, each of these locations would have 2 different solutions defined following solution of the Laplace equation.

along Γ_j . With knowledge of our end conditions at $s = 0$ and $s = 1$; $V_{0,i}$ and $V_{0,i+1}$ respectively, the linear variation of V_0 over the length of this boundary can be given as

$$\frac{dV_0}{ds} = (1-s)V_{0,i} + sV_{0,i+1} . \quad \text{Equation 29}$$

This produces a boundary condition that can be applied to the boundary segment. If the workpiece profile contains M boundary sections, then M individual boundary functions are created. Each of these boundary conditions is then assigned to their corresponding boundary ID, and the geometry is re-meshed and solution of the Laplace equation takes place.

6.6.2 A Comment on the Implementation of This Method Using the Current System

At this stage a note is required on implementing this overpotential parameter as a function of workpiece length, and is the first time that the use of the commercial FEA package has introduced critical problems. Though the software is capable of representing individual boundary conditions as a function of distance, it appears that the solver struggles with the use of such functions adjacent to each other. This is especially apparent in the export of smooth and continuous current density data as a function of workpiece boundary length. Consequently simulating using this commercial software has so far been unachievable. Work is continuing to try and reach a successful conclusion, through different techniques; however it may be that this is the limit of the current methods capabilities.

Chapter:

7 Three-Dimension ECM Simulation

This final chapter involves the development of the two-dimensional ECM simulation presented previously into a time-dependent three-dimensional ECM simulation. Whilst the theory of material removal remains the same, the practical methods used in the two-dimensional version need to be modified for a three-dimensional environment. The required development is presented, before the results of simulating the machining of a generic tool is shown.

7.1 Introduction

Up to this point, all the simulations shown have been two-dimensional simulations of the machining process. It is clear that the real-world use of such a system is limited and a simulation that allows for the machining of three-dimensional parts is a desirable option.

Simulating in 3-D is computationally more demanding and requires more developing time to become operable. However, a number of the algorithms presented in previous sections for the ECM of the 2-D profiles can be adapted and similar rules applied for a three-dimensional machining environment.

7.2 Modifications required

The step from a two-dimensional simulation to a three-dimensional one requires a number of alterations to the existing simulation code. Having said that, the principals of the process remain the same, and a number of the algorithms presented in Chapter 3, can be used, at least in part, again.

The key areas that need to be modified are:

- Establishing a 3-D FEA condition for FEMLAB
- Geometry
- Mesh
- Creation of a suitable workpiece boundary surface
- Identification of boundary surface faces
- Extraction of data from boundary faces
- Implementation of the moving boundary
- Reforming a suitable geometry

7.2.1 Establishing 3-D FEA conditions within FEMLAB

As mentioned previously, the ECM simulation is coupled with FEMLAB via a data-structure that translates the information from one to another. In order to generate three-dimensional machining, this data structure needs to be modified to declare that a 3-D FEA solution is required. The process is relatively simple, and is initiated by the declaration of a different mode within the structure. Once the 3-D mode is initialised, the starting geometry needs to be inserted into the structure. Once again, this can be achieved either through the import of a previously defined CAD geometry, or created within the FEMLAB software. The final stage is to initialise the mesh of the geometry object. For the purposes of this three dimensional simulation, a tetrahedral mesh is defined containing Lagrange, quadratic elements.

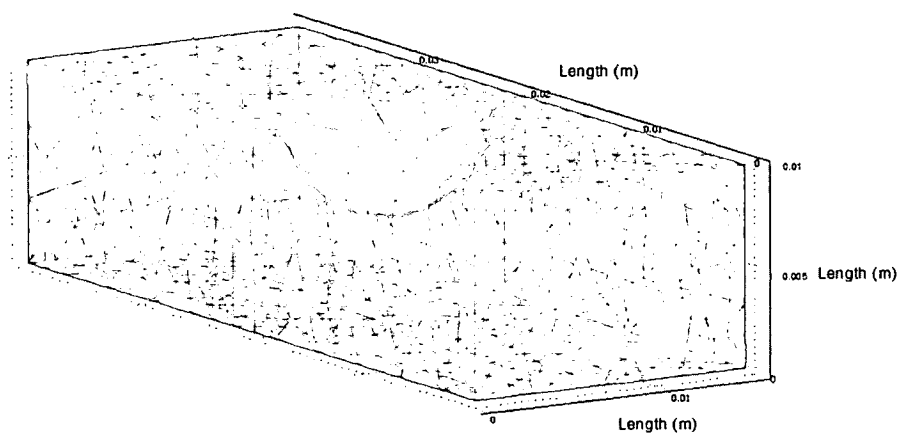


Figure 76: Image of a meshed sample geometry

With these conditions established the identification of the boundary surfaces and application of the boundary conditions can take place.

7.2.2 Creating a suitable workpiece boundary surface

Initially the workpiece boundary in this simulation consists of a single flat, rectangular polygon. Clearly this needs to be deconstructed in order to allow the movable surface required to simulate the ECM process. To achieve this information on the width and the length of the workpiece surface is extracted from our mesh object. The starting workpiece surface is identified using the method discussed previously, where the ID numbering system used in FEMLAB is exploited. By identifying this geometry face, the node points of the mesh that lie on this boundary can be extracted. At this point the points are distributed in a triangulated manner across the surface of the boundary. Due to the restrictions of the geometry shapes within FEMLAB, the workpiece boundary needs to be decomposed into square faces. In order to decompose the workpiece surface into individual surface polygons an interpolation through the mesh points is used to produce a matrix of uniform points lying on the surface. The resolution of this surface grid is defined via user inputs into the ECM simulation.

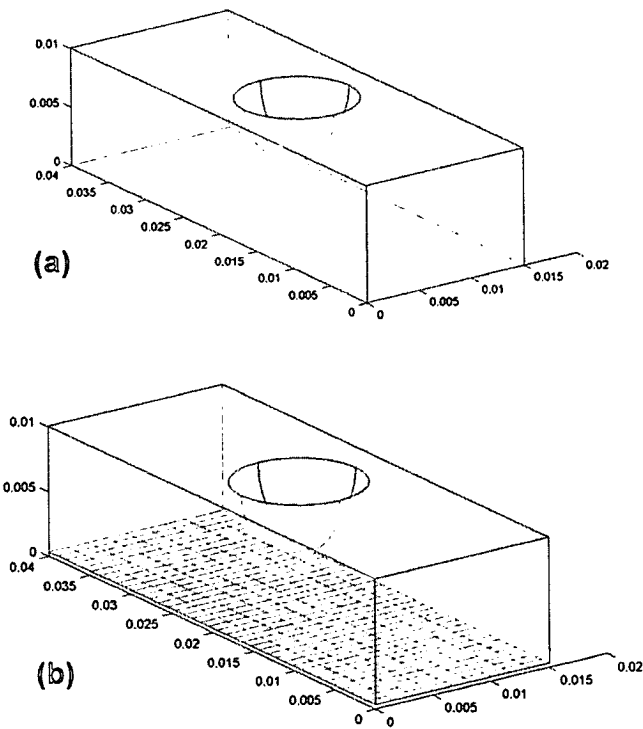


Figure 77: A sample geometry (a) before boundary gridding, (b) after gridding

With the new grid of points defined, use of a FEMLAB polygon creation tool allows the individual polygons to be generated. The starting workpiece surface is then removed and the new polygons inserted as a replacement. The subdomain is reformed (Figure 77), and the modified geometry is reinserted into the data structure.

7.2.3 Identifying the boundary geometries

As with the two-dimensional simulation, the 3-D ECM simulation needs to automatically identify and index the boundary surfaces that make up the tool, the workpiece and the side boundaries of our subdomain. The approach taken here is similar to the methods used in the previous simulation and relies on evaluation of surface normals and adjacency information.

Through evaluation of the geometry, the surface normals of each of the boundary faces and the polygon adjacency information are extracted. Again, the ID system used in FEMLAB is exploited to identify a boundary on the tool. Using this starting ID an algorithm scans and indexes all the faces that define the tools boundary surface. The side boundaries are determined by the surface normals. At this point an assumption is made that only surfaces with a normal perpendicular to the z-axis are the side boundaries. Clearly this assumption fails if simulating machining using a straight sided tool, though this failure could be resolved through a check to assess whether that tool boundary has been evaluated previously. The workpiece boundary surfaces are then identified through implication i.e. any boundary ID's not already associated with the tool or the side boundaries must lie on the workpiece surface.

The ECM simulation now contains an indexed log containing the ID's of each of the components of the machining set-up. This information is then used for the application of the boundary conditions, in the same manner as the 2-D ECM simulation.

7.2.4 Extraction of data from the workpiece surface

With a suitable geometry in place and definition of the boundary conditions complete, the geometry is then meshed and the solution of the Laplace field equation initiated. The solution is then returned to the data structure for the 3-D ECM script to extract data. As with last time, the information required for the calculation of the material removal is the current density along the workpiece. At this stage the node data of the mesh contains the current density values, though this is distributed based on the tetrahedral mesh i.e. in a triangulated manner. To enable material removal calculation at the points on the uniform grid, an interpolation method at the co-ordinates of these points is initialised. In this manner the 3-D ECM simulation generates a matrix of current density data for each of our workpiece boundary points that can be used for the material removal calculations.

7.2.5 Implementing workpiece boundary movement

The material removal calculation is based on the same methodology as presented previously with material removal taking place in a direction the normal at each of our boundary points and proportional to the current density at that point. Whereas previously a spline was fitted through our boundary points to calculate the normal, this 3-D method uses a cubic surface fit to assess the normals at this grid of points. The resulting material removal at each point is calculated and the location of the new surface boundary is created. Before the geometry can be reformed the points defining our surface need to be re-aligned to form a uniform grid. A new surface is created through the shifted points, and using the MATLAB grid-data function a new matrix of uniformly distributed points is generated.

7.2.6 Reforming a suitable geometry

The final operation to be performed in each iteration, is the reforming of a geometry that can be used for the next iteration of the ECM simulation. In the 2-D ECM simulation, this was a relatively simple task that was facilitated by reconnection of straight-line objects. In the 3-D simulation this is a more complex task, primarily due to the fact that along the base of the side boundaries a number of workpiece boundary points lie. This makes the automated generation of a suitable side boundary shape using the FEMLAB geometry primitives, difficult and

computationally demanding. The technique developed uses a system of slicing to generate the correct boundary surface.

The first task is to create a surface geometry from our workpiece points using the same method and tools as in the first iteration where the workpiece boundary was first decomposed. This surface is going to be used as the cutting plane. The second task is to create a geometry that can be sliced by this surface. This geometry consists of the tool boundary, and a flat base, with the distance between tool and flat base defined as a length that is greater than the lowest point on the workpiece surface profile.

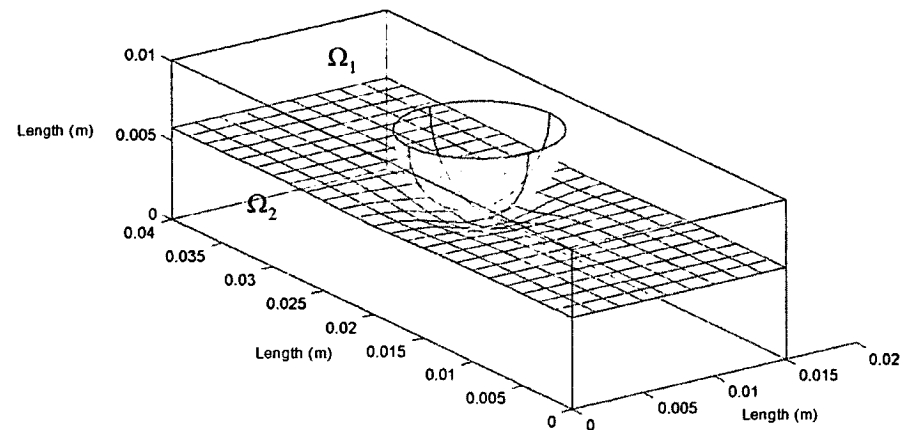


Figure 78: The cutting plane required to form the new workpiece surface and the extended geometry to be cut

Since the desired workpiece boundary surface lies completely within the secondary geometry, it can be used as a cutting plane to split the geometry containing the tool into two sections (Ω_1 and Ω_2). This splitting operation is performed using FEMLAB geometry manipulation commands. Out of these two the upper subdomain, Ω_1 is required for subsequent analysis, and is extracted back to our data structure. The second subdomain, Ω_2 , is discarded.

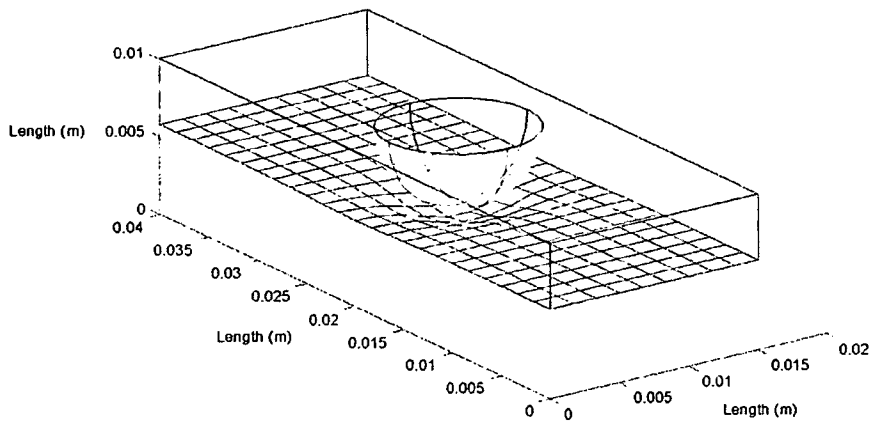


Figure 79: Removal of the lower subdomain section results in the geometry to be used for subsequent analysis

With the new geometry in place, the object is meshed, the boundary conditions reapplied and the simulation progresses to the next iteration. In this manner the three-dimensional simulation of ECM can be performed.

7.3 Example Simulation

7.3.1 Simulation Set-up

The images shown below are taken from a simulation using a half-sphere shaped tool machining a flat, titanium 6/4, workpiece (Figure 80). This tool was chosen as it demonstrates that material removal takes place correctly in the x , y and z directions. The dimensions of the geometry are shown in Figure 81.

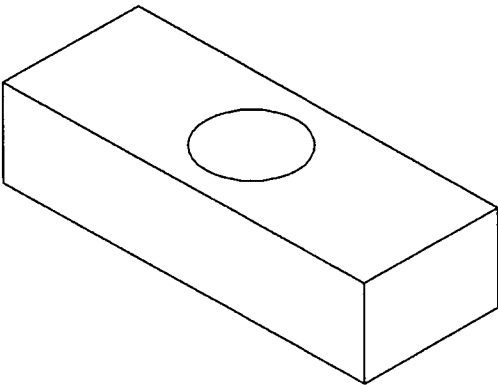


Figure 80: Isometric view of the half ball starting geometry

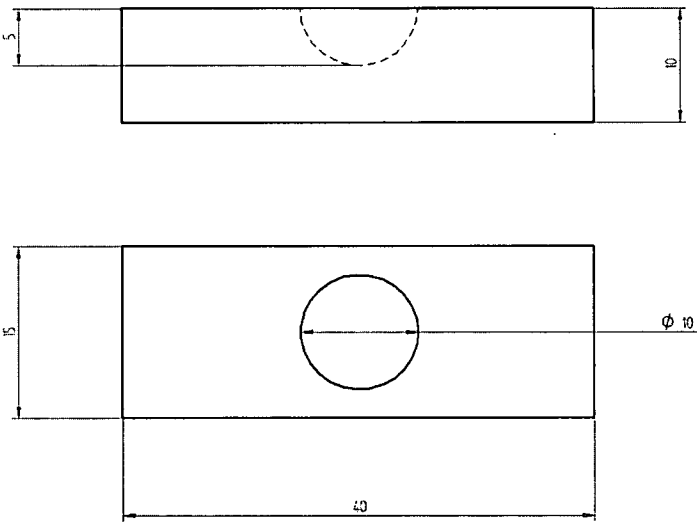


Figure 81: Side and top views of the input geometry (all dimensions in mm).

The simulation parameters used were:

<i>Component</i>	<i>Parameter</i>	<i>Value</i>
Material Properties	Atomic Mass	45.8
	Valency	4
	Density (kg m ⁻³)	4418
	Overpotential (V)	5
Experimental Parameters	Feed rate (mm min ⁻¹)	1
	Starting gap (mm)	5
	Electrolyte Conductivity (S m ⁻¹)	20
	Applied Voltage (V)	15
Simulation Parameters	Time step (s)	20
	Total Time to Simulate (s)	800
	Grid x-resolution	10
	Grid y-resolution	25

The simulation was performed on a PC with Dual Pentium 4 3.06GHz processors and 2Gb RAM.

7.3.2 Results

The total simulation time was 585 seconds for 40 iterations (0.07 iterations sec⁻¹), representing 800 seconds of actual machining.

Figure 82 shows a series of images showing the machining of the workpiece as it approaches equilibrium.

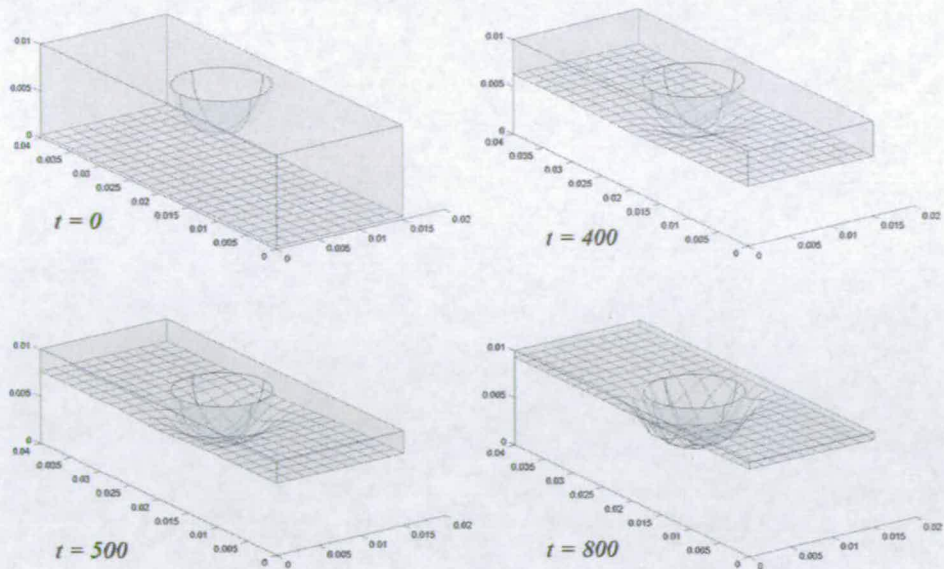


Figure 82: The 3-D ECM simulation geometry at 4 stages during machining (t in seconds; all lengths in metres.)

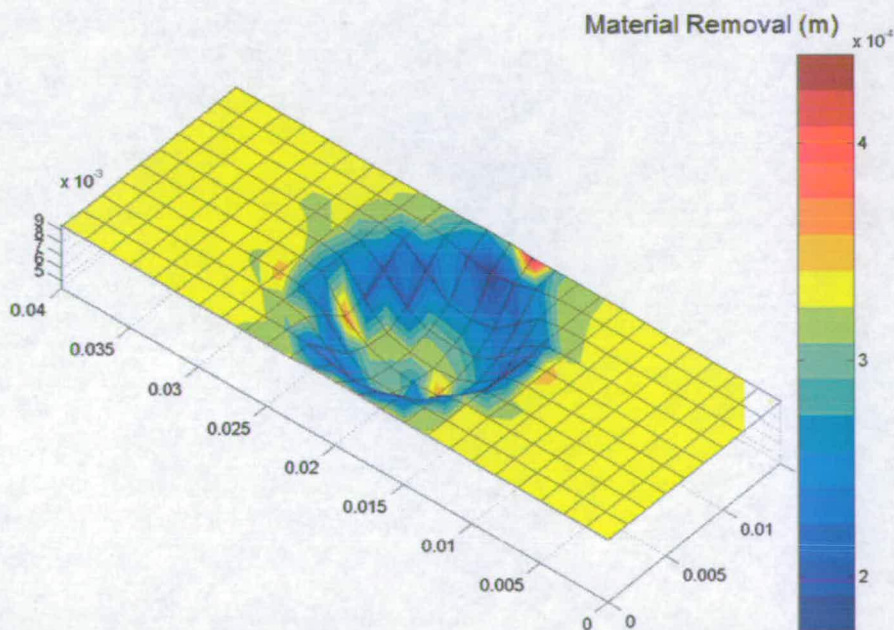


Figure 83: Surface map of the workpiece geometry at $t = 800$ seconds. The surface is coloured by material removal; all lengths in metres.

Figure 83 shows the surface of the workpiece geometry at the end of the machining run. The surface has been coloured by material removal at that time step. As

expected the areas of the highest material removal coincide with those regions that are furthest away from the tool surface. There is a minor deviation in the results, where at one point on the side of the crater is being machined. This has arisen from the resolution of the surface grid at that point being insufficient to represent the curvature of the surface.

7.3.3 Validation

The three-dimensional simulation of the ECM process has not been validated directly against experimental data. In Chapter 3, the assumptions based on the principals of the one-dimensional theory led to an accurate 2-D non-flat workpiece shape being formed, which indicates that such an assumption should produce similar results in three dimensions. It is worth noting that existing three-dimensional ECM simulations have based their material removal rates on these assumptions [73, 79, 80-82].

Without experimental validation data however, it is difficult to comment with certainty on the accuracy of this model.

7.4 Conclusions

This chapter has presented the development of a three-dimensional, time-dependent ECM simulation. Results have shown that the modifications to the two-dimensional simulation have been successful for the case of a generic tooling shape. Whilst some industrial manufacturing processes can be reduced to a two-dimensional simulation conditions, a number demand that a full, three-dimensional, life-like representation is required. This work has shown that the simulation techniques used in this research are applicable to even these industrial demands.

Chapter:

8 Conclusions and Further Work

This section reviews the work and conclusions of the thesis. In addition, the next logical stages of this work are presented in the form of further work.

8.1 Conclusions

This work demonstrated how a time-dependent simulation of the ECM process can be adapted to a number of industrial applicable scenarios. It also introduced a parameterised overpotential model that is based on characterised material data. This data was measured using a unique ultrasound measurement system developed by members of the ECM group at Edinburgh University.

The aims of this research, stated in Chapter 1, were:

- The production of a time-dependent simulation of the electrochemical machining process.
- Assessment of the applicability of this simulation to industry by investigating specific adaptations of the ECM process, including machining under non-equilibrium conditions and machining in three dimensions.
- Characterisation and inclusion of a critical process parameter, the overpotential, into a simulation of the ECM process.
- Validation of the resulting non-ideal simulation through comparisons with experimental and ideal-simulation, results.

These have been achieved via the following:

- A time-dependent two-dimensional simulation using the commercial packages FEMLAB and MATLAB has been developed. Results presented indicated the applicability of the methods used, through the simulation of ECM using a complex shaped tool. This simulation was then validated against experimental data.
- This simulation was shown to be suitable for application in a number of different industry specific variations, including a non-equilibrium

machining system, and the development of a three-dimensional simulation. Results of sample simulations for each of the methods were presented.

- The use of the ultrasound measurement system allowed the characterisation of the workpiece overpotential in a form suitable for introduction as a parameterised model into a time-dependent ECM simulation. The inclusion of the overpotential as a parameterised model was shown to be crucial to a more accurate simulation of the ECM process through the validation of the non-ideal simulation by comparison of results against experimentally obtained data and simulating using ideal conditions.

8.2 Further Work

Following on from the work presented in this thesis the author would like to propose three main areas that would help extend this research further.

Further dissolution characteristic modelling

In Chapter 5 the results of the overpotential were focused upon for this research. Also presented in this section were details of the valency, and how the ultrasound method can be used to measure the changes in this quantity during machining. With the information available, research focused on the inclusion of this parameter as a time-dependent variable could prove beneficial to the accuracy of simulations.

Inclusion of overpotential model into two- and three-dimensional workpiece simulations

With the presentation of validated results of the simulation using the overpotential model with flat workpieces, the development of simulation using this model in non-flat geometries is extremely desirable. Chapter 6 presented the theory behind implementing the parameter in non-flat workpieces, though the limitation of the implementation of function based boundary conditions, prevented simulation. If this obstacle can be overcome then the inclusion of this characteristic model can take place.

Adaptation of the three-dimensional model for industrial applications

This would require advancement of the three-dimensional model to the stage where some of the industrial adaptations presented in Chapter 4 can be implemented. In this manner the simulation approach could be used for the non-ideal, time-dependent simulation of the non-equilibrium machining of turbine blisks for example.

The successful achievement of the last two tasks may be dependent upon an alternative approach than the use of a commercially available FEA solver to perform the solution of the Laplace field equation taken here. Though this work has demonstrated with success the ability of the developed simulations to model a number of different industrial applications, the method adopted still has its limitations. In Chapter 3 the rationale behind the use of a commercial package was presented and shown to be viable for the creation of initial simulations. The first limitation of this approach was commented on in Chapter 6 owing problems in the implementation of function based boundary conditions. Finally, though Chapter 7 presented three-dimensional results for a generic shape, the tool geometry used was simple by industrial standards. The author had hoped to be able to create a more complex three-dimensional geometry more indicative of the surface of a turbine blade. This proved to exceed the geometry handling capabilities of the FEMLAB software and despite concerted efforts to overcome these constraints, the limit of this approach had been reached.

Consequently, to further this simulation work in ways stated above, the author would recommend that an in-house meshing and Laplace solver is developed. This would remove the constraints that the use of commercial software has placed on this work, and allow for more advanced representations to be formed.

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Appendix A:

Conference Paper

Time-Dependent Simulation of Electrochemical Machining Under Non-Ideal Conditions

This paper was presented by the author at the Electrocor 2005 conference held in Cadiz. It was well received and the author received the award for "Outstanding Contribution to the Conference".

Time-dependent simulation of Electrochemical Machining under non-ideal conditions

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Abstract

Electrochemical machining (ECM) is a manufacturing process based on the principles of electrolysis. It machines irrespective of workpiece hardness and, as a result, it is used in the manufacture of parts requiring the use of hard alloys such as airfoil blades. Die-sinking ECM involves a shaped tool being moved closer towards the workpiece. Material removal takes place under the influence of an electric field. Once material removal rates are equal to the tool feed rate the process is said to have reached equilibrium. At equilibrium the workpiece is an approximate inverse of the tool shape. Under ideal ECM conditions, a number of process parameters are assumed to be constant. Industrially however, conditions are rarely ideal, and it may not be desirable to machine until equilibrium. This paper presents a time-dependent simulation that includes a model of one of the changing parameters, the overpotential, which is the voltage required to drive the electrochemical reactions at the workpiece and the tool. Previous work has shown that this condition varies through the course of machining. Validation is performed against experimental results, and comparisons are made against simulation under ideal conditions.

Keywords: Electrochemical machining, ECM, simulation, time-dependent, finite-element analysis, overpotential, non-ideal, non-equilibrium.

1 List of Symbols

V_o	Overpotential	A	Area of workpiece electrode
n	Valency	κ	Conductivity
V_t	Applied voltage	I	Current

z	Gap	ρ	Density of workpiece
$\overline{dh}$	Material removed	nJ	Normal current density
F	Faradays constant = 96500 C mol ⁻¹	Ω	Subdomain
M	Molecular mass of workpiece	t	Time
		J	Current Density

2 Introduction

2.1 Background

Electrochemical Machining (ECM) is a manufacturing technique capable of shaping complex parts through anodic dissolution. It is most effectively applied when the material to be shaped is prohibitively hard for efficient machining using conventional contact techniques. It has been adopted in many areas of the manufacturing sector, including the aerospace industry where super-alloys are regularly used. It is a non-contact method that results in little or no tool wear, and ensures that there is no introduction of undesirable shear stresses in the workpiece material [1, 2]. A variety of products are manufactured using this technique, from turbine blades and blisks in the aerospace industry to microelectronics [3].

This paper discusses die-sinking ECM where the electrolyte is pumped through a gap between the tool (cathode) and the workpiece (anode), removing the products created by dissolution. During the process the two electrodes are fed closer together. After a period of machining, the material removal at the workpiece is equal to the feed rate and an equilibrium-state is reached. At this stage the workpiece is an approximate inverse to the tool shape [1].

2.2 Non-ideal conditions during ECM

Under ideal conditions, a number of process parameters are considered to be constant [1]. Industrially, however, the ECM process often cannot be considered ideal, with variations in process parameters and non-equilibrium machining requirements apparent. In non-equilibrium machining the workpiece is not machined to an equilibrium shape. The tool needs to be designed to produce the correct shape prior to reaching the equilibrium state. An example of such a process is the ECM of the trailing edge of aerofoil blades that are used in turbine engines. Consequently, tool design becomes increasingly complicated, often resulting in the adoption of a costly trial-and-error approach [4]. In an effort to reduce these costs, approaches have been developed to aid the tool design process and simulate machining. Additional work has taken place to include models of varying parameters during machining.

In the area of tool design, analytical approaches have been developed that utilise process parameters to predict a tool-shape from a desired workpiece shape. Methods include simplistic shape projection techniques [1], to more

complex conformal mapping techniques [5, 6]. These methods lend themselves to computational efficiency, however they assume equilibrium is reached and can produce unrealistic tool profiles [6].

Time dependent, numerical approaches to simulating the ECM process have also been devised. The finite-element approach has been shown to be a valid way of simulating the process and is capable of producing accurate results [7, 8, 9]. These simulations can offer workpiece shape-solutions during machining, not just at equilibrium, as well as allowing experimental parameters to be monitored over time.

Variations in process parameters can result in the deviation from predicted workpiece shapes calculated assuming ideal conditions. The conductivity (κ) of the electrolyte can vary under the influence of phenomena such as temperature change, flow path variation and hydrogen bubble generation. This variation of κ will alter the rate at which material is removed along the workpiece. Further developments have led to the inclusion of additional mathematical models to simulate some of the process phenomena that are taking place during the ECM process [10]. These include temperature and gas generation within the inter-electrode gap during machining as well as some modelling of the electrolyte flow.

Additionally, variations occur in the chemical parameters that determine the dissolution rate of the workpiece material [11]. These include the valency of the workpiece material and the overpotential required to drive the reactions at each electrode. These parameters have previously been assumed to remain constant during machining.

This paper proposes the inclusion of a parametric model of the changing overpotential into a numerical, time-dependent ECM simulation. It is believed that with the inclusion of this model a more accurate simulation can be produced. The approach demonstrated uses repeated finite-element analysis over a series of time steps allowing geometric solutions at any stage of the machining, not just at the equilibrium state.

3 Overpotential Variation During ECM

3.1 Overpotential

During electrolysis two reactions occur: an oxidation process at the workpiece and a reduction process at the tool. The oxidation process results in metal ions being displaced from the workpiece, through an oxide layer, and into the electrolyte solution. The displacement of these metal ions creates vacancies in the oxide layer, which are filled by more ions from the workpiece. The oxide layer is produced by a reaction between the workpiece material and oxygen. At the tool, a reduction process takes place, which releases an hydroxide ion. In ECM, the electrolyte is pumped between the tool and the workpiece in order to remove these ions from the system. In order to drive these electrochemical reactions at tool and workpiece, an overpotential (V_0) is required.

3.2 Characterisation of Overpotential

Research has been undertaken to characterise V_0 against measurable machining parameters for a variety of workpiece materials typical to those used industrial ECM. Typical materials include Inconel, Stainless steel and Titanium. Eqn (1) defines the relationship between V_0 and the current (I) during machining.

$$I = \frac{(V_t - V_0)A\kappa}{z} \quad (1)$$

Ultrasound techniques have been implemented to produce real-time measurement of the inter-electrode gap (z) during machining [12]. This, combined with measurement of I , and knowledge of the tool voltage (V_t), electrode area (A) and electrolyte conductivity (κ), allows the calculation of changes in V_0 during machining.

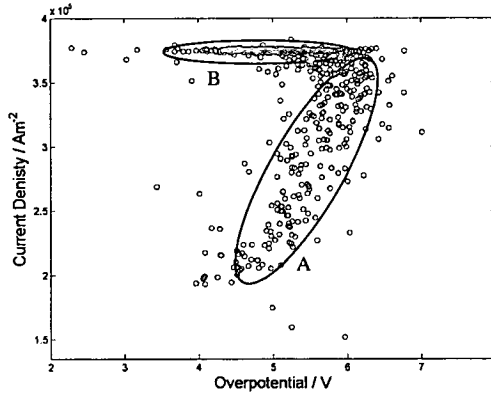


Figure 1: A typical graph showing changes in overpotential against current density. Region A shows the measurements taken before the breakdown of the oxide layer. Region B shows measurements taken once machining through the broken oxide layer.

Whilst machining in region A, shown in Figure 1, the oxide layer is of a constant thickness. The resistance is constant and the layer behaves in an ohmic fashion, producing a linear relationship [13, 14] between V_0 and J . At higher J values, as seen in region B, the rate of dissolution is increased and more ions and electrons are released. The number of vacancies produced increases and they start to coalesce. Consequently, the oxide film begins to breakdown, producing a drop in the resistance, and a reduction in V_0 . Experimentally, the tool and the workpiece are moved closer together, reducing the resistance across the inter-electrode gap. Subsequently, J increases and results in an increase of V_0 at the workpiece.

It is the V_0 increase in region A that this paper will introduce as a parametric model into a simulation of the ECM process. Models are still being developed to describe the variations in V_0 seen in region B as well as the transition between the two regions.

4 Simulation Overview

The software used for this simulation is MATLAB used in conjunction with the finite-element package FEMLAB. The geometry used represents the electrolyte gap with the upper and lower boundaries defining the profile of the tool and the workpiece. The workpiece boundary is broken down into a number of points, evenly distributed along its length. Figure 2 shows the boundary conditions applied in the model.

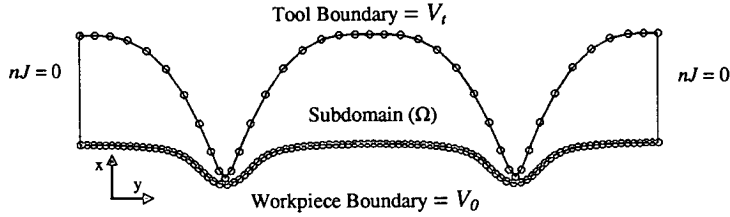


Figure 2: An example of a possible geometry with boundary conditions used in simulation.

The tool boundary is assigned V_t . The side boundaries are constrained so that the normal of the current density (nJ) equals zero. V_0 is applied as the workpiece boundary condition and varies in magnitude in the simulation in accordance with J as discussed in Section 3.2.

The simulation feed rate (f) and V_t are assigned constant values based on typical experimental settings. κ , determined through analysis of experimental electrolyte concentrations, is defined in Ω and the electric field is evaluated through solution of the Laplace field equation,

$$\frac{d^2V}{dx^2} + \frac{d^2V}{dy^2} = 0. \quad (2)$$

Analysis takes place during each time step (dt), after which the current density (J) data is extracted from points along the workpiece boundary. The material removal at each of these points ($\vec{dh}$) takes place normal to the workpiece, and is calculated using,

$$\frac{\vec{dh}}{dt} = \frac{Jm}{FM\rho}, \quad (3)$$

where n is the valency, M is the molecular mass, ρ is the density of the workpiece, and F is Faraday's constant. A spline representation is used to calculate the normals at each of the points distributed along the boundary.

$\vec{dh}$ is combined with the tool movement and the points are displaced. A spline is interpolated through the new coordinates, and a new set of evenly distributed points are defined. The geometry is re-formed and re-meshed, V_0 is re-evaluated, the new boundary condition is applied, and solution of the electric field is repeated.

The simulation can be terminated automatically based on either user defined conditions such as elapsed time, or can be dependent upon process parameters being monitored for example current values, or depth of material removed.

5 Validation

5.1 Experimental Set-up

A flat-segmented tool was positioned in the base of the machining rig and a 40x15mm Titanium 6/4 workpiece was fed towards it at a rate of 0.5mm/min whilst V_t was set at 16V. Throughout machining a 15% Chloride electrolyte ($\kappa = 20\text{Sm}^{-1}$) was pumped between the two electrodes at 16 litres/min and recycled through a tank. This flow rate is considered to be sufficiently high to minimise conductivity changes due to electrical heating and products generated during electrolysis. Machining was allowed to take place until equilibrium had been reached. An ultrasound probe is positioned behind the workpiece to measure the workpiece thickness during machining and subsequently allows for calculation of z . Real-time data was collected and stored for later comparison.

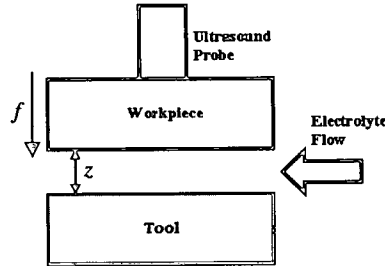


Figure 3: Overview of the machining set-up.

5.2 Simulation Set-up

The simulations were performed on a PC with Dual Pentium 4 3.06GHz processor and 2Gb RAM. f and V_t were set to 0.5mm/min and 16V respectively; n was set to experimentally obtained values. Figure 3 shows the V_0 model used

for Titanium 6/4 in a 15% Chloride electrolyte. It has been calculated using a least-squares fit through experimental data collected whilst machining in region A.

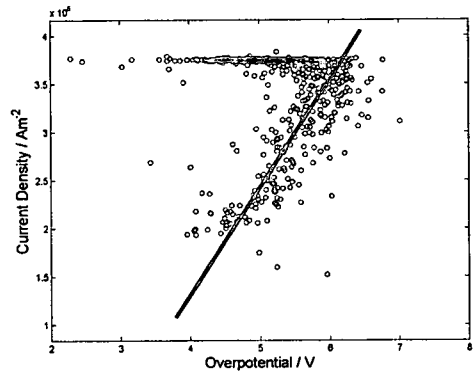


Figure 4: The model ($\Rightarrow$) used to calculate V_0 during non-equilibrium machining.

The simulated machining time was 580 seconds. For further comparison, the same simulation was performed with $V_0 = 5.3\text{V}$, the mean of the measured experimental V_0 . This provides a set of results for simulation under ideal conditions.

5.3 Results

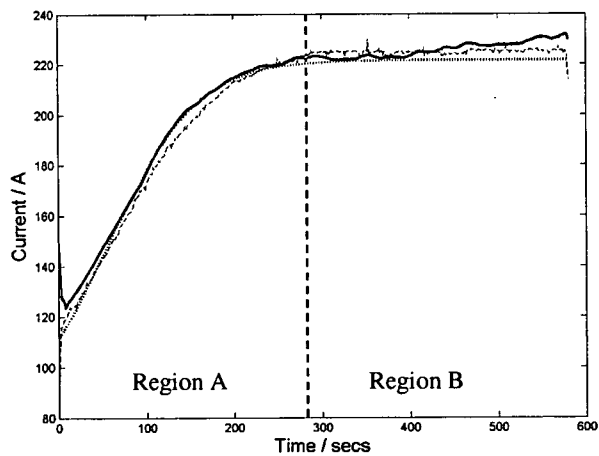


Figure 5: Comparison of I against t for experimental (---), non-ideal simulation ($\Rightarrow$) and ideal simulation (ooo).

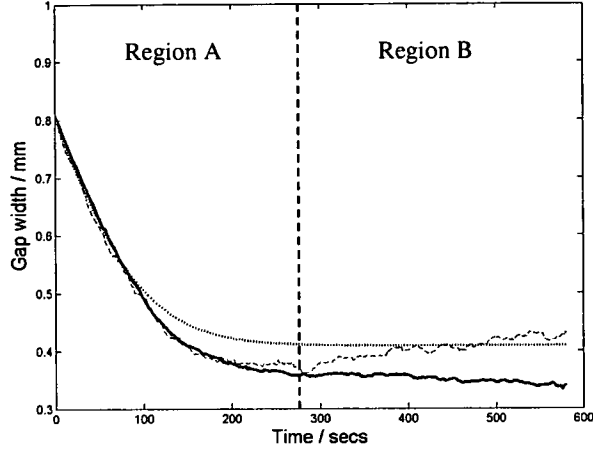


Figure 6: Comparison of z for experimental (---), non-ideal simulation (—) and ideal simulation (ooo).

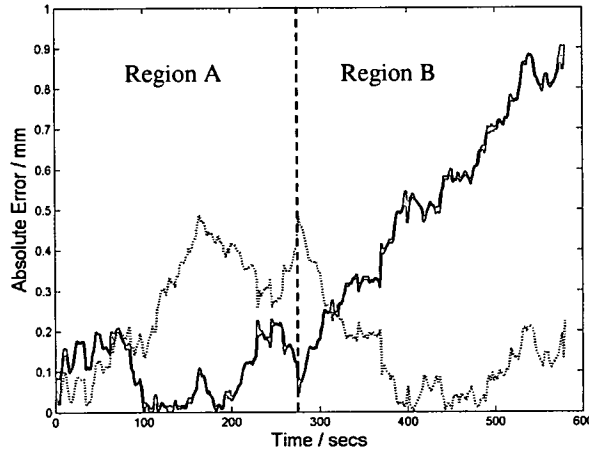


Figure 7: The error between experimental gap and non-ideal gap width (—) and ideal condition gap width (ooo).

6 Discussion

The experimental, non-ideal simulation and ideal simulation results are shown in Figures 5, 6 and 7. Figure 5 and 6 show the current transient and the gap between the tool and the workpiece surface during the machining respectively. Figure 7 shows the absolute error between experimental z and the simulated z for ideal

and non-ideal conditions. The figures also show the two V_0 regions, discussed in section 3.2. Region A is defined from experimental data and its duration is the first 270 seconds of machining. After this point, machining is taking place according to region B and the oxide layer is breaking down, resulting in a decrease in V_0 .

The current transient, shown in Figure 5, demonstrates that both the ideal and the non-ideal simulations produced similar I values whilst machining in region A. The ideal simulation I becomes constant and the non-ideal simulation I continues to increase. This is due to the continued application of the V_0 model defined for region A throughout the simulation of machining in region B.

The z vs. t graph, shown in Figure 6, shows that the non-ideal simulation closely follows the experimental data whilst machining in region A. Beyond this stage the model used is no longer an accurate representation of the changes in V_0 . The ideal simulation z initially matches the experimental data. After 100 seconds however, it indicates that z is wider than that measured experimentally, with deviations of up to 0.5mm, shown in Figure 7.

Once machining in region B, the experimental gap begins to increase as V_0 begins to decrease. Since this region is not modelled in the non-ideal simulation, z continues to decrease. The effect of this can be seen in Figure 7 where the error between experimental and non-ideal simulation z increases. The ideal simulation remains constant throughout region B.

7 Conclusions

A two-dimensional simulation of ECM using finite-element methods has been created that implements a parametric model for overpotential. The simulation is time-dependent, allowing for non-equilibrium machining to be evaluated.

The non-ideal simulation has been demonstrated and the results for simulation of machining using a Titanium 6/4 workpiece has been compared against both experimental data and results from a simulation using ideal conditions. The results for these tests show that the addition of these parameterised values produced a more accurate predication for the current and gap width during non-equilibrium machining states when the oxide layer is of a constant thickness.

Further work is required to develop the overpotential model to include the behaviour of the oxide layer as it breaks down at high current densities, as well as the application of the model to non-flat geometries.

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Appendix B:

Journal Paper

Real-time Parameterization of Electrochemical Machining by Ultrasound Measurement of the Inter-electrode Gap

*This paper was submitted and accepted for publication in the
Proceedings of the IMechE Part B: Journal of Engineering
Manufacture (Vol 221)*

Real-time parameterization of electrochemical machining by ultrasound measurement of the interelectrode gap

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Abstract: This paper discusses the development of an ultrasound technique that enables the continuous, uninterrupted collection of time-resolved data for dissolution valency, inter-electrode gap, and overpotential during electrochemical machining (ECM). These parameters, in combination with the dissolution current, give insight into the ECM process. The accuracy and expediency of this approach has been established using results collected from the ECM of the stainless steel SS410. The enhanced accuracy and resolution offered by this approach has been demonstrated through comparison with established current-time and interelectrode gap-time analysis methods. This superiority has been explained both in terms of the relative accuracy of the analysis methods and the removal of the requirement for the approximation of constant-valency machining. The resulting current-overpotential relationships are sufficiently accurate to give insight into the ECM dissolution characteristics of the steel, as well as providing an improved parameter base essential for increasingly accurate simulation of the ECM process and tool design techniques.

Keywords: electrochemical Machining, ultrasound, interelectrode gap, parameterization, overpotential, valency, realtime, tool design, simulation

1 INTRODUCTION

Electrochemical machining (ECM) is a manufacturing technique capable of shaping complex parts through anodic dissolution. It is a non-contact method that results in little or no tool wear, ensures that there is no introduction of undesirable shear stresses in the workpiece material, and gives a finished workpiece with little surface damage [1]. The technique is most effectively applied when the material to be shaped is prohibitively hard for efficient machining using conventional, contact techniques. A variety of products are manufactured using this technique, including fabrication of turbine blades and blisks as well as microelectronic components [2].

ECM provides many cost benefits: a direct saving in machining time is made compared with mechanical machining, and there is low scrap metal production and little or no tool wear. However, initial set-up costs for an ECM process are significantly greater than for leading competitive processes [3–5]. In addition to these costs, another significant drawback of the process is the difficulties involved in tool design. A simple trial-and-error approach can be adopted, although this can prove costly, especially if the part to be manufactured requires a high degree of accuracy. Steps have been taken to produce computational simulations of the ECM process in an effort to try and optimize tool design prior to actual machining [6, 7]. Additionally, direct tool design approaches have also been devised that allow the user to generate a tool shape based on a desired workpiece profile [8–10].

These simulation approaches are entirely dependent upon an accurate knowledge base of the behaviour of the dissolution parameters during

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assumed at high electrolyte flow [14, 19], and a constant value of n , typically calculated at I_∞ , using

$$I_\infty = \frac{nAFf\rho}{M} \quad (9)$$

This is often a reasonable assumption, but changes in n can occur during ECM, particularly through changes in current efficiency owing to significant competing anodic reactions at the workpiece such as oxygen evolution [16]. This method gives discrete, mean values for V_0 at intervals along the current transient.

As equations (6) and (7) are essentially the same equation, if the assumptions discussed hold, both current and gap analysis will yield identical values for V_0 .

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Figure 5 shows the behaviour of the dissolution valency throughout the course of the machining run. The data points have been calculated using equation (3). Two plots are shown, one with $p = 11$ and the other with $p = 50$ (equation (4)). This serves to highlight the effect the choice of p has on the calculated valency data. As expected, Fig. 5 shows that the use of a greater value of p results in a reduction in the noise in the dataset. However, the use of such large values of p precludes the measurement of excursions in n over short time periods, and so should be avoided in cases where these would be expected. Reassuringly, the data presented are consistent with previous observations for this material [19], with a valency averaged over time of $n = 2.1 \pm 0.1$.

Using the z data in conjunction with time-resolved V and I data, V_0 has been determined for this experiment using equation (1). The results of this procedure are shown in Fig. 6. It is immediately apparent that there is a significant variation in V_0 during the machining process. Initially, the overpotential increases during the approach phase as I increases,

machining. Many of these approaches rely on assumptions such as equilibrium (machining until the workpiece profile becomes invariant) being reached, or adoption of constant values for variables such as the overpotential – the potential used to drive the electrochemical dissolution process. A more accurate parameter base would form the basis for increased sophistication in the modelling of the ECM process, as well as provide an increased knowledge base for inverse tool design methods. Important ECM parameters include the electrolyte conductivity, the dissolution valency, and the overpotential as a function of controllable and easily measurable ECM conditions, for example, the dissolution current and applied voltage [11–13].

The chronoamperometric approach [14] to the analysis of current, voltage, and time data from ECM uses time-averaged data to produce a combined parameter for the overall machining process [15]. Time-resolved measurement of the interelectrode gap is required in order to obtain time-resolved parameterization for the course of the machining process. Attempts to provide time-resolved data include the use of a mechanical probe introduced through a hole in the tool to make contact with the workpiece surface [16] and a travelling microscope optically to observe the interelectrode cross-section [17]. The principal disadvantage of these approaches is the need to disrupt or even halt the machining process in order to provide a gap measurement. An alternative approach has been suggested previously that has presented details of an ultrasound measurement technique that potentially avoids these problems [18]. This technique allows for real-time collection of machining data, without interrupting or intruding upon the machining process. It also provides a potential advantage for machining by making closed-loop control possible.

This paper assesses the feasibility of this ultrasound approach for the measurement of the interelectrode gap and the parameterization of the ECM process by presenting data recorded across the entirety of the machining run. The results obtained using this new technique will be presented and compared against the established chronoamperometric method.

2 THEORY

This paper discusses die-sinking ECM. In this approach, the tooling electrode (the cathode) and the workpiece electrode (the anode) are positioned in a high-pressure cell, and an electrolyte is pumped through the interelectrode gap. During the process, a current is applied across the interelectrode gap and the two electrodes are fed closer together.

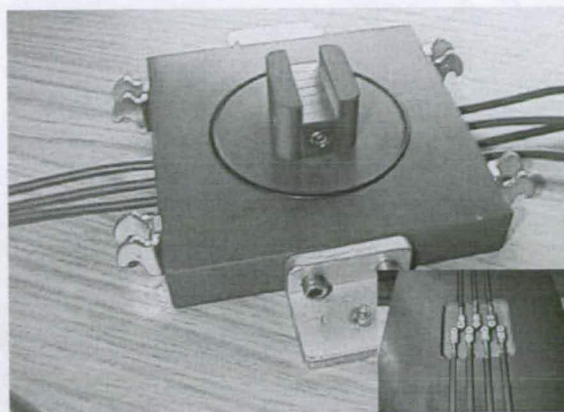


Fig. 1 Image of segmented tool (the inset is an underside view of the segment connections)

Dissolution takes place at the surface of the workpiece, with the material removal rate being proportional to the current density at the workpiece surface. The electrolyte is continually pumped between the electrodes firstly to remove the by products of the dissolution process (dissolution debris, hydrogen) from the machining area and secondly to sustain a constant electrolyte temperature, and thus conductivity in the interelectrode gap.

The system used for this investigation consists of a planar workpiece moving at a constant feed rate towards a stationary tool of the same area. The tool used is divided into seven separate coplanar electrodes (or segments) with narrow insulation separating them (Fig. 1). The segments are numbered from 1 to 7 from upstream to downstream in the electrolyte flow (Fig. 2). For the analysis used it is assumed that the current is governed by migration and also that the flowrate is sufficiently high to remove any soluble and insoluble products from the interelectrode gap, allowing constant electrolyte conductivity to be assumed throughout the experiment. If these assumptions hold, the current across the electrolyte is given by

$$I = \frac{\kappa(V - V_0)A}{z} \quad (1)$$

2.1 Ultrasound method

In the ultrasound method, an ultrasound transmit/receive transducer is placed on the top face of the workpiece (Fig. 2). This ultrasound probe allows for the measurement of workpiece thickness data, h , throughout a machining run. When these ultrasonic data are combined with a measurement of the position of the tool, w , the time-resolved measurement of the interelectrode gap is calculated using

$$z = (h_0 - h) - (w - w_0) + z_0 \quad (2)$$

For means of a comparison between actual and ultrasonic gap measurements, the initial and final gap widths can be measured using a casting agent, thus ensuring the accuracy of this analysis technique. Hence, the ultrasound method provides a time-resolved, non-intrusive gap measuring technique.

Using the recorded values of the interelectrode gap, z , in conjunction with measured values of applied voltage and current, the overpotential, V_0 , can be evaluated using equation (1), assuming a constant value of electrolyte conductivity, κ . The most appropriate current measurement is at the point of the workpiece where the gap is measured, i.e. segment 4. This method allows data describing the behaviour of V_0 to be recorded at any point during a machining run without interruption of the process, unlike the established gap measurement approaches.

In addition, the ultrasound approach also allows time-resolved measurements of the dissolution valency, n , using

$$I = -\frac{A\rho nF}{M} \frac{dh}{dt} \quad (3)$$

In order to reduce experimental noise arising from measurement of the change in height of the workpiece, dh/dt , a point-averaged gradient, p , centred at time t over time interval $(p-1)\Delta t$, where Δt is a short time period, can be used. This is given by

$$\left(\frac{dh}{dt}\right)_t = \frac{h_{(t-(p-1)/2\Delta t)} - h_{(t+(p-1)/2\Delta t)}}{(p-1)\Delta t} \quad (4)$$

This equation provides a smoothing of the dh/dt data. The degree of smoothing is determined by the value of p with the observation of real dh/dt changes inhibited over time-scales comparable with or shorter than $(p-1)\Delta t$.

2.2 Chronoamperometric method

Previous work defined the chronoamperometric method for measurement of the overpotential [14]. The rate of change in the interelectrode gap is given by

$$\frac{dz}{dt} = \frac{k}{z} - f \quad (5)$$

Using this method, equations (1), (3), and (5) are combined and differentiated, giving the equations

$$t = \frac{k}{f^2} \left[\ln\left(\frac{1 - I_\infty/I_0}{1 - I_\infty/I}\right) + \left(\frac{I_\infty}{I_0} - \frac{I_\infty}{I}\right) \right] + t_0 \quad (6)$$

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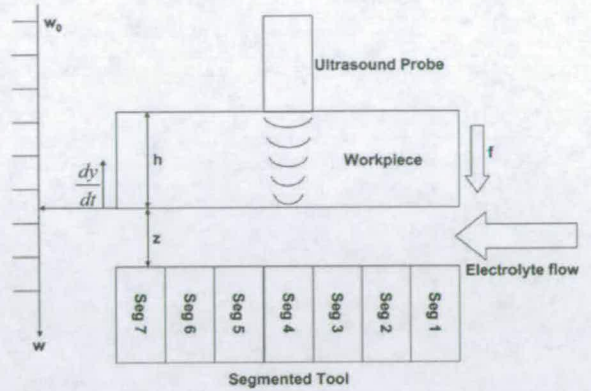


Fig. 2 Schematic diagram of the ECM system with the ultrasound probe

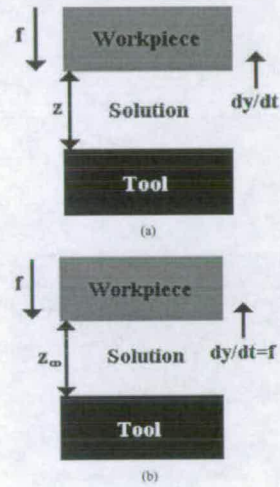


Fig. 3 Schematic of planar tool and workpiece set-up: (a) before steady state current; (b) equilibrium at steady state current. The relative movement of the electrodes is shown by arrows, and the distance between the electrodes by double-headed arrows

Equation (6) is used to fit current giving values for k/f^2 for portions of data, using the approximation that k/f^2 in a small fit region is constant. Equation (1) relates I and z and can be substituted into equation (6) to give equation (7). Parameter I_∞ is defined and measured as the constant value of I observed at long t when the dissolution rate equals the feed rate (the equilibrium current) (Fig. 3), and portions of data are fitted from a defined I_0 , t_0 to I , t . As f^2 is known, the k value calculated gives values for V_0 using

$$k = \frac{\kappa(V - V_0)M}{nF\rho} \quad (8)$$

This method assumes a constant k and hence a constant value of κ , which can generally be

assumed at high electrolyte flow [14, 19], and a constant value of n , typically calculated at I_{∞} , using

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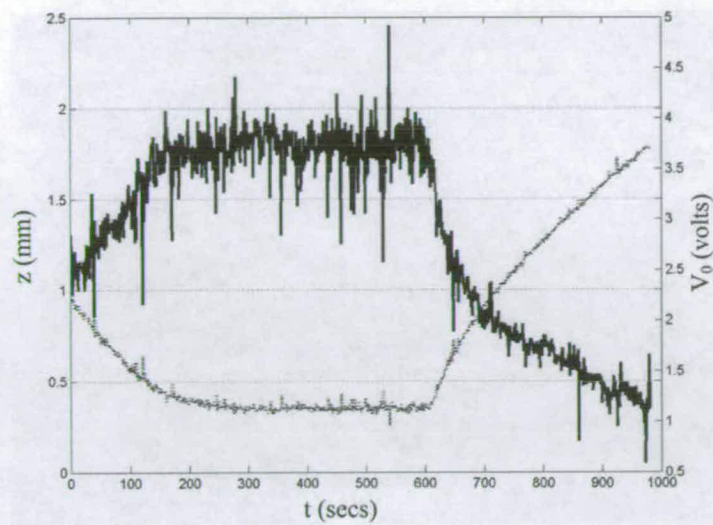


Fig. 4 Typical time-resolved plot of the variation in interelectrode machining gap (---) and overpotential (—) against time during ECM

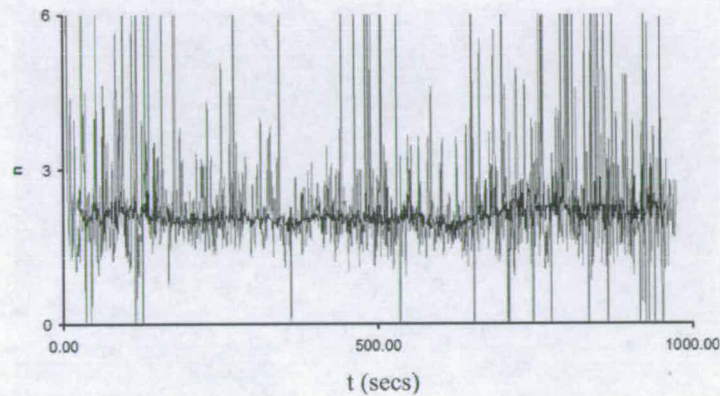


Fig. 5 Plots of variation in n against t ($p = 11$ shown in grey and $p = 50$ shown in black)

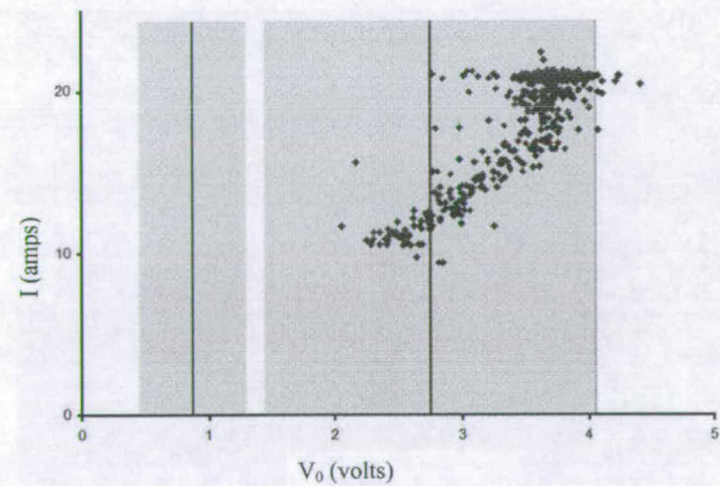


Fig. 6 Comparison of time-resolved ultrasound I - V_0 data and global I analysis and z analysis data (shaded regions)

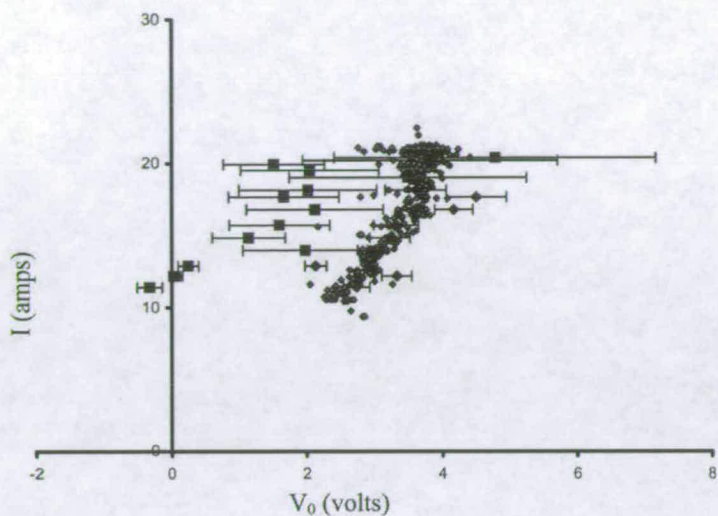


Fig. 7 Comparison of time-resolved I - V_0 data and detailed I analysis data (■) and z analysis data (◆)

and this trend then changes as machining takes place in the retract phase of the experiment, with V_0 decreasing as I decreases. This variation in V_0 with I contradicts one of the assumptions of the chronoamperometric approach, which assumes that there is a relative invariance of V_0 with I . A breakdown of this assumption could result in errors in the parameterization of the process. In order to provide a comparison of V_0 data, chronoamperometric analysis has been applied to the dataset and the results have been compared with the ultrasound method.

4.2 Chronoamperometric Results

Using ECM chronoamperometric theory, with $n = 2.14$ (equation (9)), iterative fitting of equation (6) to I - t data with $I_\infty = 21.15$ and of equation (7) to z - t data with $z_\infty = 0.32$ mm was carried out during the entire approach phase. From these data, an average value of k/f^2 was calculated, and subsequently average V_0 values were determined (equation (8)). The results of this for both I and z analysis are $V_0 = 0.86 \pm 0.42$ V and $V_0 = 2.74 \pm 1.31$ V respectively.

When comparing these average V_0 values with those obtained by ultrasound (Fig. 6), the V_0 value calculated using z analysis can be seen to be the most accurate; however, it is not surprising given the variation in V_0 with I , which violates the assumption of constant k for this analysis, that the error bar spans the entire ultrasound dataset. The V_0 value calculated using the I analysis is clearly systematically below the entire ultrasound dataset. These large errors can be attributed to the breakdown of the assumptions of constant V_0 and n (through

changes in current efficiency and/or oxidation state of workpiece metal dissolution) and to the inherent inaccuracy of the iterative curve fitting analysis compared with the simple linear relationship given by equation (1). Such large errors are unacceptable for the accurate parameterization of ECM.

4.3 Detailed chronoamperometric analysis

To assess whether more accurate I and z analysis could be performed over shorter time periods and current ranges, where the assumption of constant V_0 and n is more likely to be appropriate, the data were split into 38 s (40 point) sections and I and z analysis was carried out on each section during the approach phase. For the I analysis it was possible to fit 14 sections, while for the z analysis it was only possible to fit 9. Figure 7 shows the average V_0 values for both I and z analysis, plotted at the central I - t value of each section, compared again with the I - V_0 data from the ultrasound method. I analysis gave V_0 values that showed systematic variation from the ultrasound V_0 data, with large error bars, while z analysis gave V_0 values with much smaller error bars and reassuringly produced values broadly comparable with the ultrasound V_0 data. However, although the values obtained by z analysis were comparable, the larger errors and the inherently poorer time resolution (which results from both the requirement for multiple data points and the complexity of and hence time for analysis) still make this method markedly inferior to the ultrasound analysis technique.

This superiority of the ultrasound technique for V_0 calculations is not unexpected. The V_0 calculation

from the ultrasound technique and equation (1) is obtained by combining independent measurements of I and z and contains no valency term. Hence, these measurements are insensitive to changes in n during machining (which are often observed as a result of changes in current efficiency [16]). In addition, the chronoamperometric analysis method computes V_0 from k through equation (8). This calculation requires time averaging as well as an average valency term determined under equilibrium machining which even when valency is constant generally has an associated error of measurement of ± 0.1 . By removing this valency term from the calculations, the errors are therefore significantly reduced. The ultrasound data demonstrate that this decreased error enables sufficiently accurate data to be obtained for the investigation of trends in the I - V_0 data under ECM conditions.

5 CONCLUSIONS

This paper has presented a novel ultrasound analysis method for the time-resolved parameterization of ECM. The analysis technique has been demonstrated through analysis of the machining of an SS410 workpiece using a planer, segmented tool. The results indicate that a variation in V_0 occurs throughout machining. These results were subsequently compared with results obtained using the previous chronoamperometric method. It has been shown that the accuracy of the ultrasound analysis method exceeds that of the chronoamperometric approach.

The ultrasound method allows direct time-resolved measurement of the valency, compared with an average value calculated under equilibrium machining conditions through I_∞ from chronoamperometric analysis (I analysis). This, combined with the ability to collect continuous accurate V_0 and z data without disrupting the machining process (as with alternative techniques), demonstrates the power of this approach in the parameterization of ECM. The accurate determination of the fundamental relationships between I , V_0 , n , and t that is enabled by this approach will lead the way towards more accurate simulations of the ECM process and also aid direct tool design techniques.

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APPENDIX

Notation

A	area of the electrode, both tool and workpiece (cm^2)
dh/dt	change in workpiece height, ultrasound measurement
f	workpiece feed rate
F	Faraday constant = 96 485 C/mol
h	workpiece height, measured with the ultrasound probe
I	current (A)
k	electrochemical machining constant
M	molar mass of the workpiece (g/mol)

n	dissolution valency
Q	charge (C)
t	time (s)
V	applied voltage (V)
V_0	overpotential – the potential required to drive the chemical reactions at the electrode surfaces (V)
w	workpiece position during experiment
z	gap between the electrodes (perpendicular to planar electrode surfaces)

κ	electrolyte conductivity
ρ	workpiece density

Subscripts

i	initial value (value at time designated as initial time for fitting purposes)
f	final value (value at time designated as final time for fitting purposes)
0	value at time zero
∞	value as time approaches infinity

Q4