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Deformation Characterisations for the WEDM Contour Cut Surfaces

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***Abstract*—**The contour method is a destructive technique to measure the residual stresses. The contour method involves cutting a specimen into two halves and provides a full cross-sectional map of the residual stress acting normal to the cut surface. The cutting process is the first and most important step of the method. Any error in this step can adversely affect all the subsequent steps of the method. Wire Electric Discharge Machining (WEDM) is the best choice cutting process for the contour method. Any deviation can cause inaccuracy and uncertainty in the contour stress results. Therefore, the most appropriate cutting conditions must be selected in order to minimise undesirable cutting effects and to obtain the best surface finish. This research covers the design of a test specimen to benchmark the quality of cutting for contour method measurement. The design allows sequential trial cuts on a nominally stress-free specimen. A high yield strength mild steel (EN3B) has been selected for this research on the basis that it is widely used in industrial applications. This research helps to identify the extent, nature and causes of undesirable effects of cutting process and aids to identify the important parameters that can be used to demonstrate the quality of the contour cut to help optimise the cutting process.

***Keywords*—**Wire Electric Discharge Machining (WEDM), The Contour Method, Residual stresses, high yield strength mild steel.

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I. Introduction

THE contour method involves cutting a specimen into two halves and provides a full cross-sectional map of the residual stress normal to the cut surface [1], [2]. The cutting process is the first and most important step of the contour method. Any error in this step can adversely affect all the subsequent steps of the method. Wire Electric Discharge Machining (WEDM) has previously been identified as the best choice for the cutting step of the contour method [2]–[4]. WEDM cutting is based on a thermo-electric process, and it is performed by generating a series of electrical sparks between the EDM wire (electrode), and the component [5]–[7]. It can be applied to all electrically conductive materials, irrespective of their hardness, material strength, shape and toughness. Also, WEDM is a non-contact machining process; there is no direct contact between the electrode and the work piece during cutting. In addition, due to its non-contact nature, there is no direct force, so no mechanical plasticity is introduced by the machining process. The absence of mechanical loads during cutting also eliminates the vibration problem that often occurs with other mechanical machining methods.

Throughout the cutting process, the component is submerged in a temperature controlled deionized water tank, in order to minimise thermal effects from the cutting process. As a consequence, the work piece and the wire are actually separated by a thin film of fluid. This thin film between the work piece and the wire is sufficient to prevent an electrical short circuit, and to compensate wire vibration during the machining process. During the electrical discharge machining, sparks, initiated by a high voltage, are generated in a small gap between the cutting wire and the work piece. This develops a channel of ionised-high temperature, electrically conductive, gas (plasma), and forms a localized region of high temperature [5]–[7]. This heat results in localized melting and vaporisation of work piece material. The molten and vaporized material forms small deposits on the wire, and on the work piece surfaces. On cooling, the solidified material generates spherical debris particles, and these particles are carried away from the spark gap with dielectric liquid. The evacuation of eroded particles by the pressurised fluid is called the flushing process. Pressurised water is injected from top and bottom nozzles. Efficient flushing and removal of metal particles (chips) from the thin film of fluid (in the working gap) can help to sustain a stable machining environment. A proportion of solidified material is immediately re-deposited on the work piece surfaces as a recast layer because it was not completely expelled by dielectric fluid flushing [8]–[10]. During cooling and solidification of that layer, the microstructure and the material properties can be altered, both within the newly-formed layer and in the heat-affected zone [11], [12]. Thus, the quality of the cut surface is highly dependent on the cutting conditions (such as the cutting parameters, debris flushing and the nature of the dielectric fluid). During the cutting process, the wire is continuously fed from a spool held between upper and lower guides. Hence always fresh wire is involved in the process. The straightness of the wire is adjusted by applying a tension force to the wire. Wire tension aims to reduce the wire vibration and deflection which could affect the quality of the cut surfaces.

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Error! Reference source not found. illustrates the WEDM process.

Figure 2(a) shows a schematic representation of a test specimen undergoing cutting by WEDM. The drawing and annotations help to explain the terminologies used throughout this paper. Metal is removed by the wire slowly traversing, simultaneously in both horizontal and vertical directions, in the direction of the cut. In **Figure 2 (b)** the 'start of the cut' refers to the location where the wire begins to cut the specimen, whilst moving in the horizontal direction. The 'end of the cut' refers to the location where the wire finishes cutting the specimen, whilst moving in the horizontal direction. The 'wire entry' refers to the top surface entry of the wire when it is moving in the vertical direction. The 'wire exit' refers to the bottom surface exit of the wire when it is moving in the vertical direction. The 'wire contact length' is the segment of the wire that is enclosed by the specimen material, during cutting, and is therefore always of a length equivalent to the thickness of the specimen [4].

The accuracy of the contour method is mainly reliant on the quality of the cut [13]. It is assumed that any deviation of the newly created cut surfaces has occurred solely because of the elastic relaxation of residual stresses acting normal to the plane of interest prior to the cutting. Therefore, for the cutting processes the following criteria must be fulfilled**:** a) cutting should be flat at the plane of interest and a minimal quantity of material should be removed; b) the width of any material removed by the cutting process (the kerf) should be constant; c) the cutting process must not induce any stress on the cut surface and does not modify the original residual stresses; d) the cutting process should not induce plastic deformation. In summary, the ideal cut would have zero width, induce no stresses and allow no plasticity at the tip of the cut [2]. As mentioned earlier, at present WEDM is the best choice cutting process for the contour method [14], [15]. Any deviation from the ideal contour cutting criteria can cause inaccuracy and uncertainty in the contour stress results. Therefore, the most appropriate cutting conditions must be selected in order to minimise undesirable cutting effects and to obtain the best surface finish [16]. To date, the extent, nature and causes of undesirable effects have not been fully investigated, and there is no commercial or published guidance available on how to select good cutting conditions for contour stress measurement. This paper describes the tasks done in this research to address this deficiency in knowledge. It involves the designing test specimens that are easy to manufacture and which are suitable for conducting a series of contour trial cuts on WEDM machine to test the effects of changing process parameters. This research also covers the investigation of the quality of the contour cut surface. This research also covers investigation of the issues arising from how the specimen is restrained during the cutting process, the reproducibility of a 'good' surface finish when using WEDMs and the merits of using different diameters of wires, based on a common wire material. For this experimental evaluation, specimens nominally free of initial residual stress were chosen for several series of cutting trials. By performing a cut on stress-free material, the expected ideal cut surface should be perfectly flat. Any deviation from this can then be identified as an artefact of the WEDM cutting process [2]. In this study, the form of the averaged displacements of both mating surfaces was presented and compared by means of graphical representations, alongside the quantitative values- root mean square (RMS) deviations for both the displacement and the stress data points, magnitudes of inferred residual stresses and three dimensional roughness measurements.

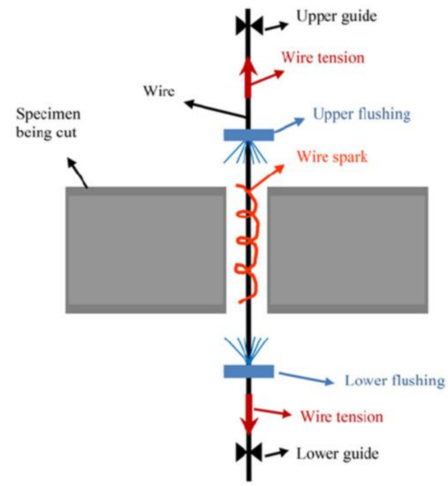


Figure 1 Through-thickness view showing the flushing and wire tension during WEDM process [4]

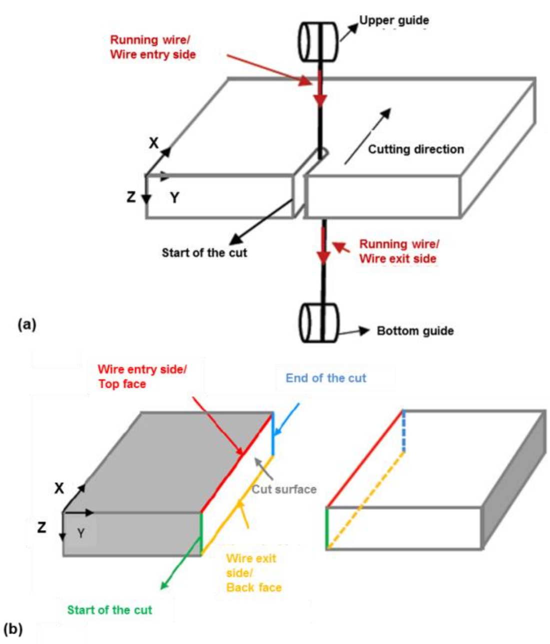


Figure 2 (a) Schematic representation of a test specimen being cut by WEDM and (b) labelled edges of cut parts [4]

II. Specimen Preparation

In this study, one sample thickness and one material type were tested. The material type chosen was high yield strength mild steel (EN3B) on the basis that they are widely used in industrial applications. The material specifications for a high yield strength mild steel (EN3B) are given in **Table I**. Each specimen was machined (using conventional cutting tools) into rectangular bars 245 mm long, 50 mm wide and 25 mm thick. The top and bottom surfaces of the specimens were milled to get flat parallel sided surfaces to ensure "near perfect" flushing conditions, when bringing the WEDM flushing nozzles immediately adjacent to the specimen surfaces. The specimens were specifically designed to be fixed at one end, using M10 bolts fitted directly to the machine baseplate as illustrated in the photograph shown in **Figure 3**.

Figure 3 Photograph of the specimen (245 mm long, 50 mm wide and 25 mm thick)

In order to eliminate machining stresses, the specimens were stress relieved using appropriate heat treatments according to the material type. The specimens were placed in a vacuum furnace at 600°C for about an hour. In order to make sure they were close to a nominal stress-free state after heat treatment, the surface residual stresses were measured using an XSTRESS 3000 X-ray diffractometer (Stresstech Oy, VALAKOSKI, Finland), fitted with a 3 mm diameter collimator. The X-ray radiation source was Cr K-α, with a wavelength of 2.2897 Å at 270 W power and 10 mA current. The position of the peak arising from the {211} diffracting plane was at a 2θ angle of approximately 156.1°. The $\sin 2\psi$ technique [17] was applied using 10 scans with a range of $-45^o \leq \psi \leq 45^o$ psi angles, in order to determine the error margins for each stress measurement. These measurements were conducted for ten points on the top and back face of the specimens, along the plane of each cut. **Figure 4** shows the specimen being measured for surface residual stresses, using X-ray diffraction. The surface residual stress measurements showed compressive and tensile stresses within a range of 15 to 20 MPa for all the mild steel specimens. It suggested that the mild steel specimens did not contain internal residual stresses large enough to affect the quality of the cut surfaces.

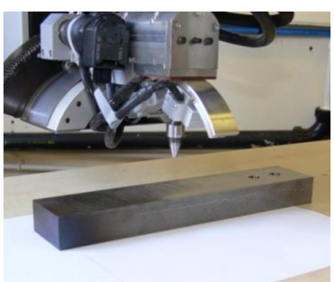


Figure 4 Specimen being measured for the surface residual stresses using X-ray diffraction

TABLE I THE CHEMICAL COMPOSITION AND MATERIAL PROPERTIES FOR HIGH YIELD STRENGTH MILD STEEL

Mild Steel (En3B)	Wt.% (Remaining Fe)	C	Mn	S	P	Si
		0.13-0.18	0.7-0.9	0.05	0.05	0.1-0.4
	Material Properties	Young's modulus (GPa)		Poisson's ratio		Yield strength (MPa)
		210		0.3		370

III. METHODOLOGY

The work consisted of two broad experiments. The first experimental design included three cuts where the remote end of the specimen was clamped, and the end to be cut was left unclamped, hence unrestrained cutting conditions were used. Particular attention was given to maintaining the optimum control, and repeatability of the cutting conditions for each trial cut. In order to initiate the experiment, a standard set of WEDM cutting parameters (as recommended by the machine manufacturer) were used to perform the cuts without any manual intervention. Following the results of the first experiment, a second experiment was designed, again with just the remote end of the specimen clamped. However for this experiment local constraint was provided at the end of the specimen to be cut, hence this time restrained cutting conditions were used. This extra support, in the form of restraining ligaments of material, was provided at the start of the cuts, to help control the quality of the cuts, and to minimise the WEDM cutting artefacts found in results from the first experiment. This second experiment included five cuts. Restraining ligaments of material were created by starting the cut from pilot holes located a small distance from one side of the test specimen. Two different ligament lengths were compared to see which offered the better restraint during cutting. In addition to this, some modifications were made in the setting of the WEDM cutting parameters based on previous cut results. The second experiment also investigated the effect of wire diameter (two sizes) on the quality of the cut surfaces.

IV. EXPERIMENTAL DETAILS

A. The First Experiment - Unrestrained Cutting Conditions

The first experiment involved making cuts on high yield strength mild steel (EN3B) with unrestrained cutting conditions. A rectangular specimen with dimensions 245 mm long, 50 mm wide and 25 mm thick, was used for the first experiment. The first experiment comprised of three cuts. This series of cuts was performed on a mild steel specimen named as MS-A, using an Agie Charmilles FI 440 CCS WEDM. The cuts were undertaken with a cut length of up to 50 mm and a wire contact length of 25 mm. During WEDM cutting, one end of the specimen was clamped, whilst 25 mm thick slices were removed from the free end. Each new cut was positioned 25 mm away from the previous cut plane, in order to maintain the surface finish quality and surface integrity of each surface, and to prevent one cut from influencing another. The first cut was performed using a standard set of WEDM cutting parameters (designated S5 on the machine), with a 0.25 mm WEDM wire diameter. There was no manual intervention. The second cut was performed as a repeat of the first cut, using all the same cutting conditions, as a means of measuring the repeatability of the process. The third cut was performed with the cutting wire moving in the opposite direction to the first cut. All the other cutting conditions were a repeat of those used on the first cut. This cut was performed in order to explore the effect of electro-magnetic forces during cutting. **Figure 5** shows annotated photographs of various stages of the first experiment.

a) Unrestrained specimen before cutting **b) Specimen mounted on WEDM** **c) Unrestrained specimen after cutting** **d) Cut parts** **e) Contour surface measurements**

Figure 5 Photographs showing various stages of the first experiment

a) Restrained specimen before cutting **b) Specimen mounted on WEDM** **c) Unrestrained specimen after cutting** **d) Cut parts** **e) Contour surface measurements**

Figure 6 Photographs showing various stages of the second experiment

B. The Second Experiment - Restrained Cutting Conditions

The same specimen design, specimen material type and WEDM were used for this second experiment as were used in the first experiment. During each cut one end of the specimen was clamped and cuts were performed using the same procedures as in the first experiment. The experiment was composed of two series of cuts using two specimens named as MS-B and MS-C, giving five cuts altogether. **Figure 6** shows annotated photographs of various stages of the second experiment. Following the results of the first experiment (unrestrained cuts), the following modifications were made in the design of second experiment. Firstly, the cuts were performed with restrained cutting conditions and started from pilot holes formed using an EDM hole drilling machine. The centre of the first pilot hole was placed 25 mm away from the free end of the cantilever specimen. A second pilot hole was drilled in line with the first, at a pitch of 25mm between centres. Secondly, two different ligament lengths of material, between the pilot hole and edge of the specimen, were trialled in an attempt to introduce restraint during cutting. In addition to this, to reduce the effects of electromotive force (details are provided in Section VII-Discussion on experimental results) during the cutting process, some modifications were also made in the electrical parameters of WEDM such as 'A (microsecond) - Energy duration of the pulse (voltage and current)' and 'TAC (microsecond) - Short A time'. These WEDM parameters are directly related to the energy of the spark. Decreasing A and TAC values decrease the energy of the spark. Reduction in energy of spark provides help to evacuate the eroded particles and can improve flushing conditions [18]. Lastly, the effects of using two different wire diameters, based on a common wire material, were also explored with an aim to improve the quality of the cut surface finish. Further details about the both series of cuts are given below.

Restrained cuts – series 1

The first series of the second experiment-restrained cuts was performed on a mild steel specimen named as MS-B. It consisted of three cuts MS-B-1, MS-B-2 and MS-B-3. The cuts were started from pilot holes 1.8 mm in diameter, with each hole centre positioned 2.5 millimetres away from one side, along the plane of the cuts, thus leaving a ligament of 1.6 mm of material, to provide constraint whilst cutting. The first pilot hole was placed 25 mm away from the free end of the cantilevered specimen. The spacing between each pilot hole was 25 mm. Having completed each cut, the wire was stopped, leaving a 2.5 mm ligament of material intact, at the opposite side of the specimen. Then, transverse cuts were performed along the long axis of the specimen, to intersect with the end of the contour cut and release the 25 mm piece. The first cut MS-C-1 was performed using a standard set of WEDM cutting parameters (designated S5 on the machine) with A = 0.6 µs and TAC = 0.3 µs values. The cut was performed with 0.25 mm diameter wire using restrained cutting conditions created by use of a pilot start hole. The second cut MS-C-2 was performed with a 0.1 mm diameter wire and a standard set of WEDM cutting parameters (designated S3 on the machine with default A = 0.2 µs and TAC = 0.1 µs). This cut was performed to try and improve the quality of the cut surface by using a thinner wire diameter, than for cut MS-C-1. The third cut MS-C-3 repeated the MS-C-2 but with reduced A = 0.1 µs and TAC = 0.05 µs values. The cut was performed using wire of 0.1 mm diameter. This cut was performed to assess the quality of the cut by using a smaller wire diameter, in addition to a further reduction in A and TAC values for the WEDM cutting parameters.

Restrained cuts – series 2

The second series of the second experiment for restrained cuts was performed on mild steel specimen labelled MS-C. It consisted of two cuts MS-C-1 and MS-C-2. The cut MS-C-1 was performed at 25 mm away from the free end of the mild steel MS-B specimen. It was started from 1.8 mm diameter pilot hole. The centre of the pilot hole was placed at 5.9 mm away from one edge of the specimen thus leaving a 5 mm ligament of material. The cut was performed all the way through the width of the specimen. The cut was performed using the standard set of WEDM cutting parameters (designated S5 on the machine), and without any manual intervention. These cuts were performed using 0.25 mm wire diameter. The ligament length was increased from the 1.6 mm used on the first series restrained cut MS-B-1, to 5 mm, with the aim of providing additional support during the cut. The cut MS-C-2 was performed using the same cutting conditions as the cut MS-B-1 with the exception that the cut was performed approximately at mid length of the specimen, in order to provide a similar stiffness on both sides of the plane of the cut. Details of all the WEDM contour cuts performed in this study are given in **Table II**.

Table II Details of all the WEDM contour cuts performed in this study

	Cut ID	Cut description
Unrestrained cuts	MS-A-1	Cut on mild steel 0.25 mm wire diameter A=0.6, TAC=0.3
	MS-A-2	Repeat cut as MS-A-1
	MS-A-3	Cut in opposite direction, cutting conditions same as MS-A-1
Restrained cuts	MS-B-1	Cut on mild steel 0.25 mm wire diameter 1.6 mm ligament length A=0.6, TAC=0.3
	MS-B-2	Cut on mild steel 0.1 mm wire diameter 1.6 mm ligament length A=0.2, TAC=0.1
	MS-B-3	Cut on mild steel-Agie-S3 0.1 mm wire diameter 1.6 mm ligament length A=0.1, TAC=0.05
	MS-C-1	Cut on mild steel 0.25 mm wire diameter 5 mm ligament length A=0.6, TAC=0.3
	MS-C-2	Cut on mild steel 0.25 mm wire diameter Similar stiffness A=0.6, TAC=0.3

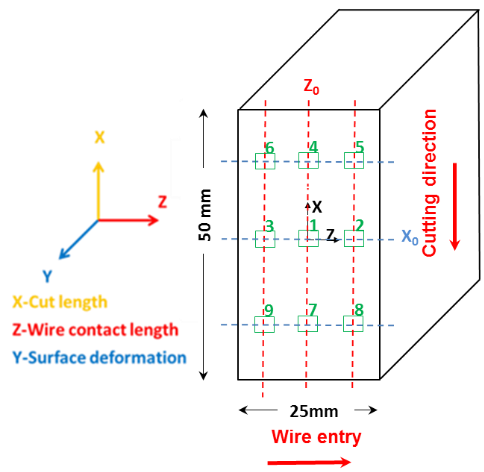


Figure 7 Shows the positions of lines (X_0 along the thickness of the specimen and Z_0 along the cut length) and shows nine different locations for 3D roughness measurements (8 mm square area was considered for the each patch) on the cut parts, X-axis 'cutting direction', Y-axis 'out of plane', Z-axis in the direction of wire feed. The origin is at the centre of the block

V. Measurement of the Cut Surfaces

A. *3D displacement measurements*

After WEDM cut, the cut parts were left in a temperature-controlled metrology laboratory for a minimum of six hours to reach thermal equilibrium with the laboratory environment. The three dimensional (3D) topography of each surface cut was measured using a Mitutoyo Crysta plus 547 CMM fitted with a 3 mm diameter Renishaw PH10M touch trigger probe. The three spatial coordinates of each point, on a 0.5 mm square grid pattern on the cut surfaces were measured. The perimeters of the surfaces were also measured, for use in FE modelling.

B. *3D roughness measurements*

Three dimensional (3D) surface roughness measurements were taken over both mating surfaces of each cut, using a confocal microscope. Roughness parameters, S_q (the root-mean-square), S_a (the arithmetic mean) of the absolute height, and RSm (the mean width of the roughness profile element), were used in the analysis.

These parameters are universally recognised and most widely used [19]. These measurements were conducted over 8 mm square patches, in nine specific locations on each cut surface. The locations of all the 8 mm square patches are identified in **Figure 7**. The mean values of each of the three roughness parameters were calculated for each cut surface.

VI. WEDM cut Surface evaluation criteria

Each cut surface was evaluated on the basis of the following criteria:

- Whole surface topography of both parts of the cuts was examined using 3D mapping methods, in order to get an overall assessment for the quality of the cut, and to identify any symmetric features.

- The averaged displacements of both mating surfaces for each individual cut were calculated and analysed.
- The averaged displacements of both mating surfaces were also analysed using 'thick' line profiles. For each thick line profile, five displacement measurement line profiles were extracted across a 2 mm width. The mean values of the five measurement points were then calculated. Displacement values for the thick line profiles were extracted along the wire direction, and along the cutting direction, at the positions of X_0 and Z_0 respectively. The thick line profile designations (X_0 and Z_0), and their locations, are defined in **Figure 7** . These thick lines were used to calculate the maximum and minimum height variations of the contour profiles. These calculations were performed for eight cuts but only two cuts results are presented in this paper due to the limitation of space.
- The averaged displacements for each cut were also used to performed 3D linear elastic FE analyses, using the ABAQUS FE code, in order to estimate apparent stresses associated with the cut that would contribute to a contour measurement. For building the 3D model, one half of the cut was built first, by extruding the measurements of the perimeters of that half of the cut. For the stress analyses of each cut surface, the cut face was meshed with 0.5 mm × 0.5 mm linear hexahedral elements (type C3D8R). The averaged topographic measurements for each cut were inverted with respect to the height (Y) coordinate, and these data were used as the boundary conditions in the FE model. Finally, elastic FE analyses were performed to obtain the stress distribution associated with the cut. This map was used to assess the errors in stress across the cut surface introduced by the cutting process. In order to understand it clearly, only three colours were chosen within the range of ±20% of yield strength to represent the stress map and the exceeding values from the range were represented in black and grey colours. The stress values exceeding from ±20% of yield strength were of concern, and were minimised in order to make a good quality of the contour cut.
- The 3D surface roughness parameters: S_q, S_a and RSm, metrics at the defined reference positions, were recorded for each part of the cut surfaces. The details about the locations for taking the measurements on the cut parts are given in Error! Reference source not found..
- The root mean square (RMS) deviation for both the displacement and the stress data points were calculated to quantify the RMS variations for each cut.

VII. Results

During the first experiment, all unrestrained cuts were performed with the intention to evaluate the quality of the cut from a contour measurement point of view. The quality of the cuts was assessed by comparing selected characteristics of the cuts, based on relevant measurements and calculations. **Table III** to **Table VI** captured salient features of the unrestrained cuts on the mild steel specimen. **Table III** shows the maximum and minimum heights, and peak to valley variations of the averaged displacements for the contour cut MS-A-1. The variations in displacements are observed along the wire direction (Z-direction) and in the cut direction (X-direction), and are from - 8 µm to 5 µm and -2 µm to 5 µm respectively. The displacement variations are greater varying along the cut direction than the wire direction. This shows that the cut has asymmetric features. The peak to valley variations along both the directions are calculated: these are 13 µm and 7 µm respectively to recognise the overall variations in both the directions. Maps of the averaged displacements and stresses from the cut MS-A-1 are represented in **Table VI**. The averaged displacement map for the cut has positive values for displacements at the middle of the cut, and negative values for those along the edges, which confirmed the convex bowed form of the cut surfaces. The averaged displacement profile was used to produce a stress map using FE modelling. The corresponding stress map for the cut surface therefore shows compressive stresses at the middle of the cut surface and tensile stresses along the edges. The stress map also shows larger stress gradient along the direction of the cut than along the wire direction. The stress profile also shows high values of compressive stress approaching the wire entry edge of the specimen. It shall refer to this as the "flared edge effect" which is produced by wire entry into the specimen. The root mean squared (RMS) values for stress and displacement variations across the area of the cut surface were also calculated and are listed in the **Table IV**, that is a stress of 59 MPa (16 % of yield strength) and displacement of 3 µm respectively. Thus, the cut surfaces are not flat but possess many topographical features that do not cancel out after averaging the profiles of both sides. These 'symmetric' deformation features can introduce high apparent stress variations in a contour measurement. Three-dimensional surface roughness measurements were taken over each cut surface using a confocal microscope. The measurement details are also tabulated in **Table V**. Values of S_q and S_a for the clamped side are 3.4 µm and 2.6 µm, and for the free side are 3.7 µm and 2.9 µm respectively. The S_q and S_a values for the clamped side were found to have slightly lower values indicating a less rough surface than the free cut side. The cut MS–A-2 was performed to quantify the repeatability of the cutting process. Hence, it was performed under conditions as close as possible to those used for the first cut MS-A-1. The second cut MS-A-2 contains very similar surface features as the first cut MS-A-1. No significant difference was found, in the RMS values for displacement and stress variations, between either of the cuts. It is confirmed therefore, that there is high precision in repeatability performance, and in the reproducibility of surface finish using the WEDM cutting machine. For the cut MS-A-3, the direction of cutting was the opposite of that used in the first two cuts. The cut MS-A-3 results are shown in **Table III** to **Table VI**, from which again shows very similar surface features as the first two cuts. Therefore, it is confirmed that formation of represented contour surface features are unrelated to the cutting direction.

The second experiment examined restrained cuts with the aim of improving the cut surface quality achieved in the first experiment that used unrestrained cutting conditions. The quality of the cuts was assessed by comparing key characteristics based upon measurements and calculations. Characterisation tables (from **Table III** to **Table VI**) for these cuts, summarise key features of the cut surfaces. They are discussed below and comparisons made with the unrestrained results from the first experiment.

Having the restraint led to a reduction in the averaged displacement variations and stress errors for the cut MS-B-1. On the other hand, surface features such as flared edges at the wire entry side, the bowed form of the surface profiles, and asymmetry in both sides of the cuts, were seen in both MS-B-1 and MS-A-1. However, these features are reduced in MS-B-1. The cut MS-B-2 was performed using restrained cutting conditions with a 0.1 mm diameter wire (note MS-B-1 used 0.25 mm wire). Averaged displacement variations and associated stresses were reduced. However, flared edges at the wire entry side, the bowed form of the surface profiles and asymmetry in both sides of the cuts were seen in both MS-B-2 and MS-B-1. Conversely, less surface roughness was observed on cut MS-B-2 than on MS-B-1 because of the smaller wire diameter used. Improved values were found in RMS variations for displacement and stress errors for the cut MS-B-2 when compared to MS-B-1. The cut MS-B-3 repeated MS-B-2 but with reduced values of cutting parameters A and TAC. From comparison it is seen that the averaged displacements from both sides of the cut were not improved. The associated stress errors were also found to be slightly larger than those from cut MS-B-2. So, to summarize, the quality of the cut surface MS-B-1 was improved by providing the restraint along the plane of the cut in comparison to the unrestrained cut MS-A-1. The quality of cut MS-B-2 was further improved by reducing the wire diameter and reduction in WEDM cutting parameters A (from 0.6 µs to 0.2 µs) and TAC (from 0.3 µs to 0.1 µs). However, a subsequent reduction in WEDM cutting parameters A (from 0.2 µs to 0.1 µs) and TAC (from 0.1 µs to 0.05 µs) for the 0.1 mm diameter wire gave no additional improvement. The surface topography of all three (first series of) restrained cuts (MS-B-1, MS-B-2 and MS-B-3) exhibited similar but reduced surface features to the unrestrained cut surfaces.

In the second series of the restrained cuts, the cut MS-C-1 was performed on a mild steel specimen (MS-C) using restrained cutting conditions as shown in **Figure 6** notably the pilot hole ligament length was increased from those used on previous restrained cuts (from 1.6 mm to 5 mm), to provide added support during cutting. An improved quality of the cut surface was not achieved by increasing the ligament. The following cut MS-C-2 used the original ligament length (1.6 mm), and reduced the material stiffness mismatch across the cut plane (i.e. cantilever dimension p was increased from 25 mm to 50 mm). **Table III** to **Table VI** compare the surface quality of the cut MS-C-2 with MS-C-1 and MS-B-1. For the cut MS-C-2, the displacement variations, and associated stress errors, were less than those found on cut MS-B-1. Moreover, the cut surface features such as asymmetry in both sides of the cut surfaces, and bowed form of the surface profile, were slightly improved compared to MS-B-1 cut. This suggests that the bowed deformation shape of the “free” side is related to the stiffness of material being cut away (note change in cantilever dimension, p, from 25 to 50 mm). Also, the quality of cut MS-C-2 can be further improved by reducing the wire diameter and reduction in WEDM cutting parameters A (from 0.6 µs to 0.2 µs) and TAC (from 0.3 µs to 0.1 µs) as shown in the results of MS-B-2 cut surface.

Table III Represents the results for the maximum and minimum height, and peak to valley variations of the averaged displacements for MS-A-1 and MA-A-2 cut surfaces using the thick lines

Averaged displacement, µm				
Cut name	**MS-A-1**		**MS-A-2**	
Surface variations / Cutting directions	X (cutting direction)	Z (wire direction)	X (cutting direction)	Z (wire direction)
Min	-8	-2	-9	-1
Max	5	5	5	6
Peak to valley range	13	7	14	7

Table IV Represents the root mean square (RMS) deviation for both the displacement and the stress data points

Name of the cut	Averaged displacement of both the sides, µm (RMS)	Stress error, MPa (%yield) (RMS)
MS-A-1	3.0	59(16)
MS-A-2	3.6	60(16)
MS-A-3	3.5	55.5(15)
MS-B-1	2.3	52(14)
MS-B-2	2	47(12.5)
MS-B-3	2.3	54(14.5)
MS-C-1	2.3	49(13)
MS-C-2	2.0	43(11)

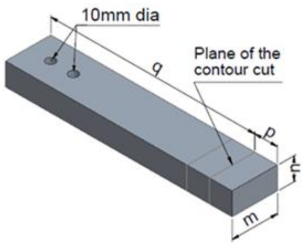
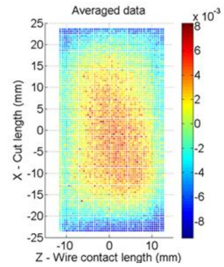
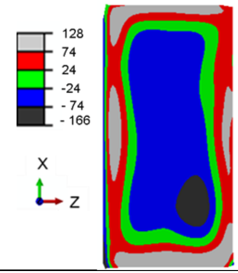
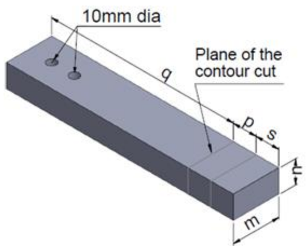
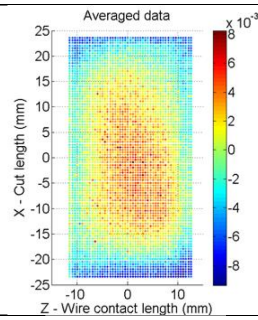
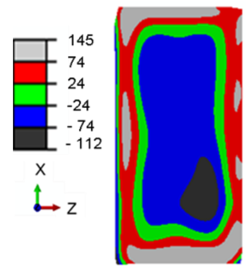
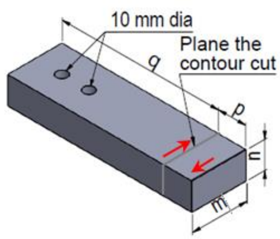
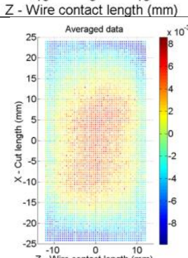
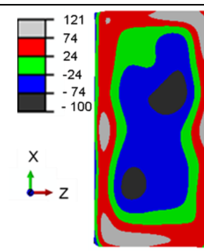
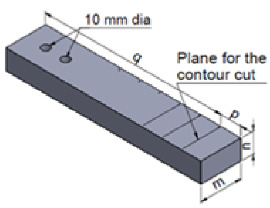
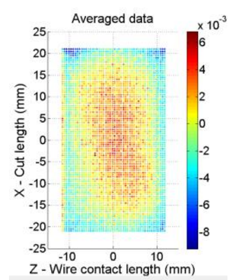
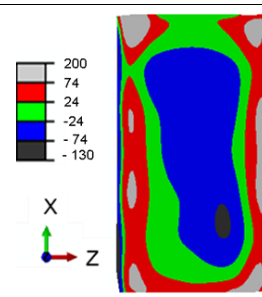
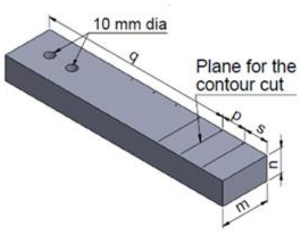
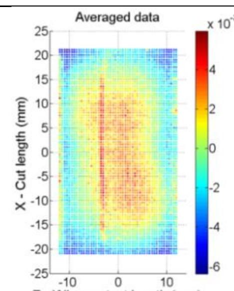
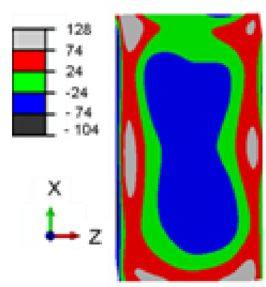
Table V Represents three dimensional (3D) surface roughness measurements for all the cut surfaces

Name of the cut	Clamped side, µm			Free side, µm		
	RSm		Sq, Sa	RSm		Sq, Sa
	X (cutting direction)	Z (wire direction)		X (cutting direction)	Z (wire direction)	
MS-A-1	130	150	3.4, 2.6	110.0	130.0	3.7, 2.9
MS-A-2	130	150	3.3, 2.6	120.0	130.0	3.4, 2.6
MS-A-3	145.0	130.0	3.3, 2.5	126.0	134.0	3.3, 2.5
MS-B-1	128.0	124.0	3.5, 2.6	131.0	147.0	3.7, 2.7
MS-B-2	131.0	121.0	2.5, 1.8	133.0	122.0	2.5, 1.8
MS-B-3	120.0	130.0	2.3, 1.8	102.0	131.0	2.3, 1.8
MS-C-1	135	136	3.6, 2.7	135	136	3.6, 2.7
MS-C-2	115	148	3.3, 2.6	125	142	3.3, 2.5

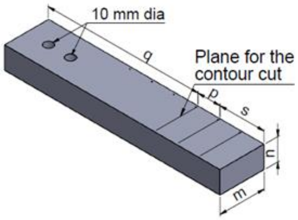
VIII. Discussion on Experimental Results

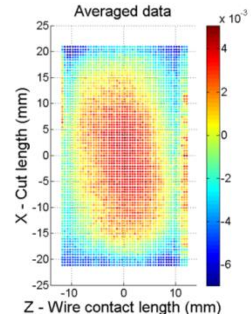
For the first experimental results, the maximum and minimum heights and peak to valley variations of the averaged displacements for the contour cuts MS-A-1 and MA-A-2 are calculated and the results are represented in **Table III**. These results show that the second cut MS-A-2 contains similar variations as the first cut MS-A-1. It is confirmed therefore, that there is high precision in repeatability performance, and in the

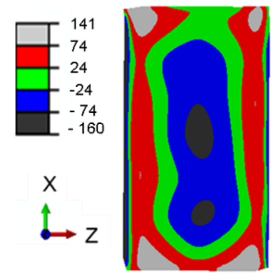
TABLE VI REPRESENTS SPECIMEN GEOMETRY, MAPS OF AVERAGED DISPLACEMENT AND STRESS FOR ALL THE CUT SURFACES, WHERE M REPRESENTS CUT LENGTH, N REPRESENTS THICKNESS, AND P AND Q REPRESENT CANTILEVER DIMENSIONS. ALL DIMENSIONS ARE IN MILLIMETRES

Name of the cut	Position of the cut	Averaged displacement profile	Stress map for the cut surafce (MPa)
First experimental results for unrestrained cuts			
MS-A-1 m = 50 n = 25 p = 25 q = 195			
MS-A-2 m = 50 n = 25 p = 25 q = 170			
MS-A-3 m = 50 n = 25 p = 25 q = 119			
Second experimental results for restrained cuts			
MS-B-1 m = 45 n = 25 p = 25 q = 220			
MS-B-2 m = 45 n = 25 p = 25 q = 195			

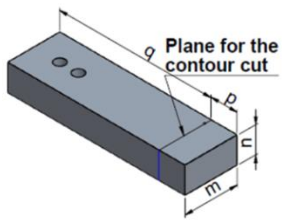
MS-B-3
m = 45
n = 25
p = 25
q = 170

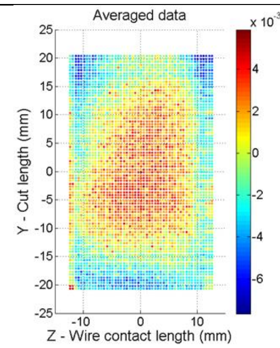


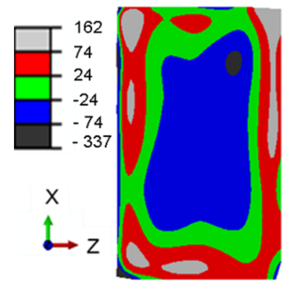




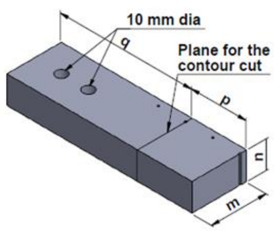
MS-C-1
m = 42
n = 25
p = 25
q = 145

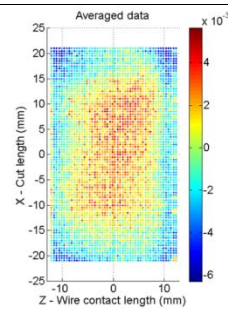


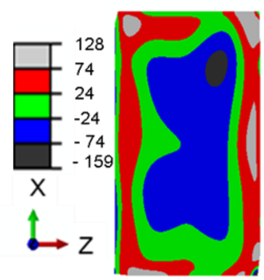




MS-C-2
m = 45
n = 25
p = 50
q = 120







reproducibility of surface finish using the Agie WEDM cutting machine. Results of this first experiment also revealed the following features of the cuts: In all cut surface results, “flared edge effects” were commonly found along the wire entry side of the cuts. This is because during the WEDM process, the corners and edges of the work piece significantly deteriorate, possibly because this is where the electric field is least uniform. High electrical energy increases the discharged pulse [20], [21] which results in a high erosion rate along the edges and causes a high value in displacement variations. These effects are further investigated in the second experiment by varying some of the electrical parameters of the WEDM and using two different WEDM wire diameters. High values of displacements across the edges of the cut surfaces result in the calculation of high values of stress in contour analysis for the respective locations. These stresses can be compressive or tensile dependent on the displacement values. The ‘bowed form’ of the cut surfaces occurred in all the cuts. The formation of this cutting artefact is influenced by the WEDM cutting parameters, as well as the material type. A suggested hypothesis to explain this effect is the higher degree of magnetisation that a mild steel material incurs, in response to the applied electro-magnetic field generated by the current pulses during WEDM cutting. The mild steel specimen concentrates a magnetic field within itself, and this affects the distribution of the magnetic flux density, during the flow of current through the brass cutting wire. So, because the magnetic permeability of mild steel is significantly higher, and more during the WEDM cutting, the wire cannot maintain an axisymmetric distribution of the magnetic flux, or a uniform current density around its axis. Therefore, looking at the wire in cross section, the magnetic flux density in the upper portion of the wire, is higher than that in the lower portion. Thus, the resultant electromagnetic force generated in the wire is magnetically attracted to, and directed towards, the mild steel work piece [22]. This causes wire vibration, wire deflection (dislocation) and excessive material removal during the cut. These inaccuracies of the cutting process can be improved by reducing the effects of the electro-magnetic force induced during the cutting process of the mild steel specimen. These effects can be reduced by lowering the supply current during the cutting processes [23]. It may also be important to demagnetise steel components before cutting to minimise these effects, noting that this procedure is recommended practice for wire machining ferritic materials [24]. Asymmetric features were found on both sides of all the cut surfaces. Features might be influenced by the specimen material type as well as clamping conditions during the cutting. It is quite possible that during cutting the free side (unclamped) moved, and so contributed to asymmetric features on the parts. Thus, it would be worthwhile investigating the cutting process whilst providing extra support to prevent any movement of the free side during cutting. All the cut surface features discussed above were observed on the averaged surface profiles of each cut. Since these features are symmetric, they cannot be eliminated by averaging in the contour method deformation analysis. If caused by artefacts, symmetric features are highly undesirable on contour surfaces because they mimic the effects of residual stress, and thus introduce errors in its determination. The surface roughness values were found similar for each cut. However, the surface finish of the cuts can be improved by optimisation of the WEDM cutting parameters, as well as by using a thinner wire diameter. In conclusion, the first experiment cutting trials show that surface deformation characteristics in a mild steel specimen can be reproduced using WEDM. This confirmed the repeatability in performance, and the reproducibility of surface finish of the WEDMs. These results also confirmed that formation of represented contour surface features is unrelated to the cutting direction.

Results from the second experiment for restrained cuts reveal the following features: The quality of the cut surfaces were improved by providing a restraint along the plane of the cut compared to results from the unrestrained cuts. This resulted in improved averaged displacement variations and a reduction of associated apparent stress errors. By reducing the wire diameter from 0.25 mm to 0.1 mm and reduction in WEDM cutting parameters A (from 0.6 µs to 0.2 µs) and TAC (from 0.3 µs to 0.1 µs) were further improved the quality of the cut surface. But further reduction in WEDM cutting parameters (A from 0.2 µs to 0.1 µs, and TAC from 0.1 µs to 0.05 µs) for the 0.1 mm wire made little difference. The cut surfaces displayed less surface roughness when a thinner wire diameter was used for the cutting process but little improvement in the artefacts contributing to apparent stress errors. Changing the ligament length from 1.6 mm to 5 mm (increasing restraint during cutting) did not improve the quality of the cut surface. A similar stiffness, on both sides of the plane of the cut, slightly improved the bowed displacement variation results in the mild steel cut surfaces. However, the effects of these features can still be observed on the topography of the cut surfaces, and do contribute to stress errors. Flared edge effects at the wire entry sides were seen on the cut surfaces in all restrained cut results, as in previous unrestrained cuts results. These contribute to high stress errors along the cut surface edges and emphasise the importance of using sacrificial layers when near to surface stresses are of interest.

In summary, the cutting conditions used to perform the MS-B-2 cut (as shown in **Figure 8**) gave a better surface finish compared to all other cutting conditions used for unrestrained and restrained cuts performed on the mild steel during the experiment. At The Open University, UK this work is still continuing and expanding for testing and evaluating different types of material and varying the cutting conditions systematically. Similar designs of specimen with larger cross-section dimensions could also be used to examine the influence of size (wire contact length and cut length).

IX. CONCLUSIONS

The following conclusions are drawn from the work carried out in this research.

- A test specimen design for contour method cutting trials has been developed (see **Figure 8**) that can be used to perform trial cuts to optimise WEDM cutting conditions for contour residual stress measurement. A stress-free rectangular specimen with dimensions 245 mm long, 50 mm wide and 25 mm thick allows multiple trial cuts to be performed in the same set up. During WEDM cutting, one end of the specimen will be bolted to the bed of the WEDM machine, whilst 25 mm thick slices are removed from the free end. “Restrained” cutting conditions can be simulated by starting cuts from a pilot hole (1.8 mm diameter) situated 2.5 millimetres away from the side of the beam (leaving a ligament of 1.6 mm) to provide constraint whilst cutting. The cut will be stopped 2.5 mm away from the opposite side of the specimen giving a cut length of 45 mm and a wire contact length of 25 mm.

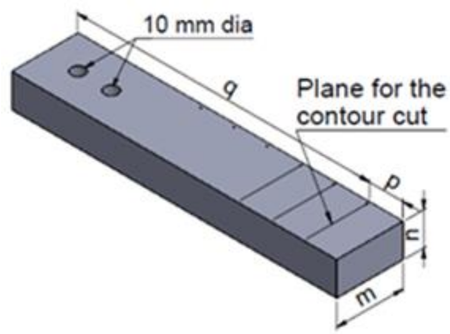


Figure 8 The proposed geometry for the benchmark specimen (245 mm long, 50 mm wide and 25 mm thick)

- In all cut surface results, “flared edge effects” were commonly found along the wire entry side of the cuts implying the need for adding a “sacrificial” layer at the wire entry side prior to contour cuts.
- Wire start topographic artefacts were observed in all cuts, again implying the need for adding a “sacrificial” material at the wire start face of a contour cut.
- In unrestrained cutting conditions, a convex bowed form of the cut surfaces was found, however, these bowed form of the surface profiles, were improved in restrained cutting conditions with a similar stiffness on both sides of the plane of the cut. This suggests that the bowed deformation shape is related to the stiffness of material being cut away. Further investigations are to be required to fully understand the origin of these “bowed” features.
- Many issues related to the quality of the cut surfaces being used as unrestrained and restrained cuts have been identified in this study. The quality of the cut surfaces for was improved by providing a restraint along the plane of the cut and resulting in improved averaged displacement variations.
- The study has also confirmed high precision in repeatability performance, and in the reproducibility of surface finish using the WEDM cutting machine.

- A thinner wire diameter gave a better quality of surface finish (lower roughness) for cuts, but made little difference to the topographical artefacts (bowing, wire start and flared edges) contributing to apparent stress errors in a contour analysis.

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