Towards good practice guidelines for the contour method of residual stress measurement

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Published in *The Journal of Engineering*; Received on 22nd May 2014; Accepted on 7th July 2014

Abstract: Accurate measurement of residual stress in metallic components using the contour method relies on the achievement of a good quality cut, on the appropriate measurement of the deformed cut surface and on the robust analysis of the measured data. There is currently no published standard or code of practice for the contour method. As a first step towards such a standard, this study draws on research investigations addressing the three main steps in the method: how best to cut the specimens; how to measure the deformation contour of the cut surface; and how to analyse the data. Good practice guidance is provided throughout the text accompanied by more detailed observations and advice tabulated in Appendix.

1 Introduction

Residual stresses are defined as self-balanced stresses that exist within a body in the absence of external loading. Residual stresses are inevitably generated during fabrication processes; they interact with imposed stresses during service, and affect the structural integrity of engineering components [1, 2]. Reliable knowledge of residual stresses is essential in order to investigate the root cause of degradation mechanisms, carry out structural integrity assessment for safety-critical components, optimise the design of manufacturing routes and validate residual stress predictions.

There is a wide range of measurement techniques available for characterisation of residual stresses in engineering components [3]. The choice of the technique depends on a number of factors; for example, the material and geometry of the component being measured, the resolution and depth to which residual stresses must be determined, the number of components of the residual stress tensor to be measured as well as the cost and availability of the measurement technique.

Standard procedures or good practice guidelines have been developed for the most commonly used and well-established measurement techniques and these instruments help practitioners to make reliable and repeatable residual stress measurements; for example X-ray diffraction [4, 5], neutron diffraction [6–8], hole drilling [9, 10] and magnetic methods [11]. The specification for a standard test method for the incremental slitting method is under preparation [12].

The contour method was invented in 2001 [13] and is emerging to become a powerful technique for mapping residual stresses in engineering structures. It uses equipment that is widely available in workshops and can produce a two-dimensional (2D) map of the residual stresses acting in a direction normal to the plane of interest. Recently, the capability of the technique has been extended to measure more than one component of the stress tensor by using multiple cuts [14, 15] and by using it in tandem with surface residual stress measurement techniques [16, 17]. However, the contour method is still young and a standard or code of best practice has yet been published.

A new programme of research has been undertaken at the Open University in the UK aimed at improving the reliability of the contour method through seeking answers to fundamental questions related to the three main steps in the technique:

- How to cut the specimens?
- How to measure the deformation contour of the cut surfaces?
- How to analyse the measured deformation data?

This paper sets out our current state of understanding of the contour method, obtained from specific research studies addressing the above questions. We attempt to provide guidance on good measurement practice using this technique throughout the text and provide more detailed observations and advice tabulated in Appendix.

2 Contour method

The contour method is an attractive technique for measuring residual stress in engineering components because it is simple to apply, it uses standard workshop equipment, and it gives a 2D map of residual stresses acting in a direction normal to a plane or surface of interest [13]. However, applying the method does result in destruction of the body. The technique is based on elastic stress relaxation through removal of material and can be applied to thin and thick heavy section structures. Although the method is susceptible to error if significant plasticity develops during cutting or stress redistribution, it has the advantage of being insensitive to the changes in microstructure resulting from, for example, welding thermal cycles. These attributes make the contour method a powerful tool for characterising residual stresses in components found in the nuclear and conventional power plant, aerospace structures and engines and petrochemical and transport industries.

2.1 Measurement steps

The theoretical basis of the contour method is Bueckner's elastic superposition principle [18]. 'Step A' in Fig. 1 shows the distribution of residual stress acting in the z-direction across the depth of a plate at mid-length. In 'step B', the plate is cut into two parts along the surface of interest. This results in elastic deformation of the cut surface owing to relaxation of the distribution of residual stress field acting normal to the surface. The deformed surfaces (the contours) are then measured. The virtual stresses which would be required to force the deformed surfaces back to their uncut shape are calculated in 'step C'. This is achieved by applying the average measured deformation contour from 'step B' to the cut face of a finite element (FE) model of the cut component in a linear elastic stress analysis. The stress distribution in 'step A' is the linear superposition of the stress state in 'step B' and 'step C' [13]. Therefore the basic steps of the contour method are: specimen cutting, surface profile measurement and data analysis (including FE modelling).

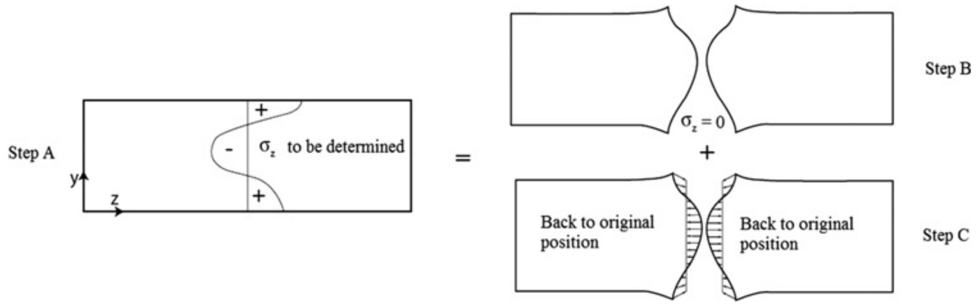

Fig. 1 *Schematic drawing illustrating the principle of the contour method for the residual stress distribution $\sigma_z(y)$ across the depth of a plate*

2.2 Assumptions

In the contour method, any deviation in the shape of the cut surfaces from the intended cut profile (i.e. deformation) is assumed to have occurred because of the elastic relaxation of residual stresses acting normal to the virtual surface of interest prior to the cut [13]. Therefore it is necessary to cut the body using a machining technique that:

(a) follows perfectly a defined surface profile;
(b) has zero cut width;
(c) does not introduce additional residual stresses; and
(d) does not introduce plastic deformation.

Deviations from any of the above idealised cutting conditions can introduce errors – sometimes of significant magnitude – in the contour method residual stress measurement [13, 19]. It is therefore of crucial importance to understand the factors that exacerbate excursions from the ideal cutting conditions, to assess how significant these are in terms of errors in measured stress and to discover

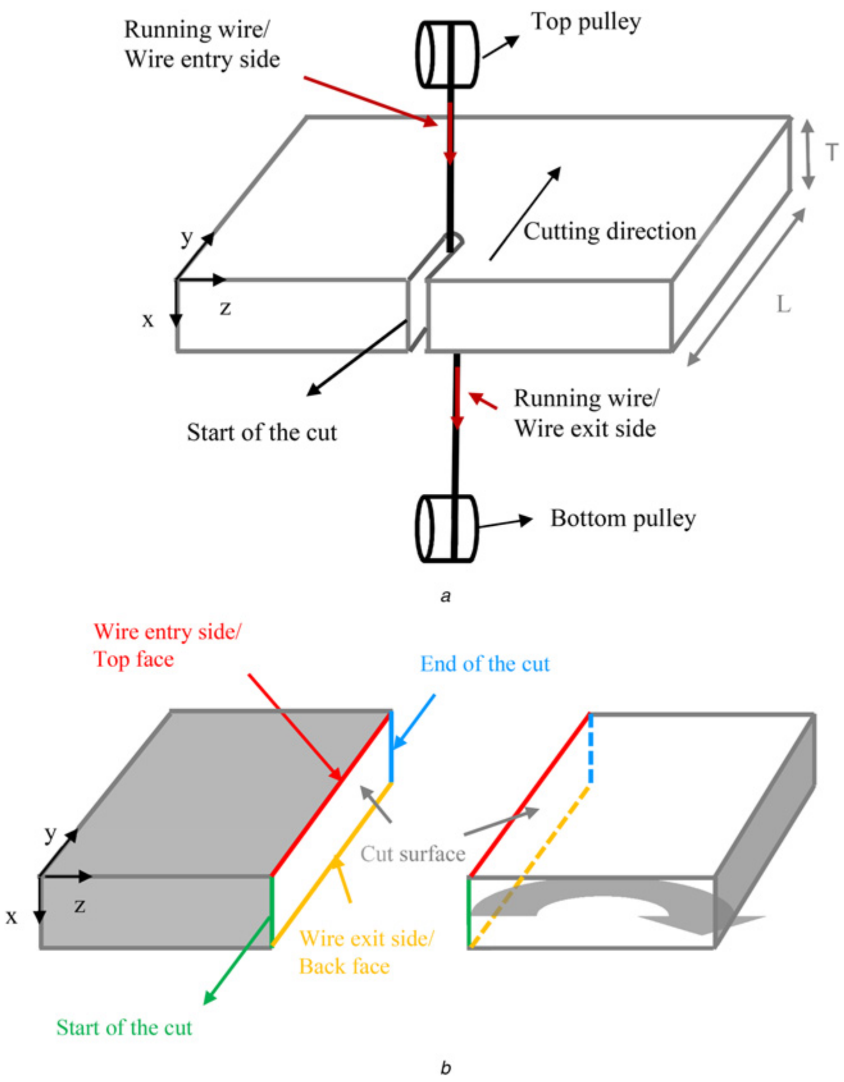

Fig. 2 *Schematic drawing of a test specimen that is being cut by WEDM*
a Schematic drawing of a component being cut by WEDM
b Labelled edges of cut parts

doi: 10.1049/joe.2014.0134

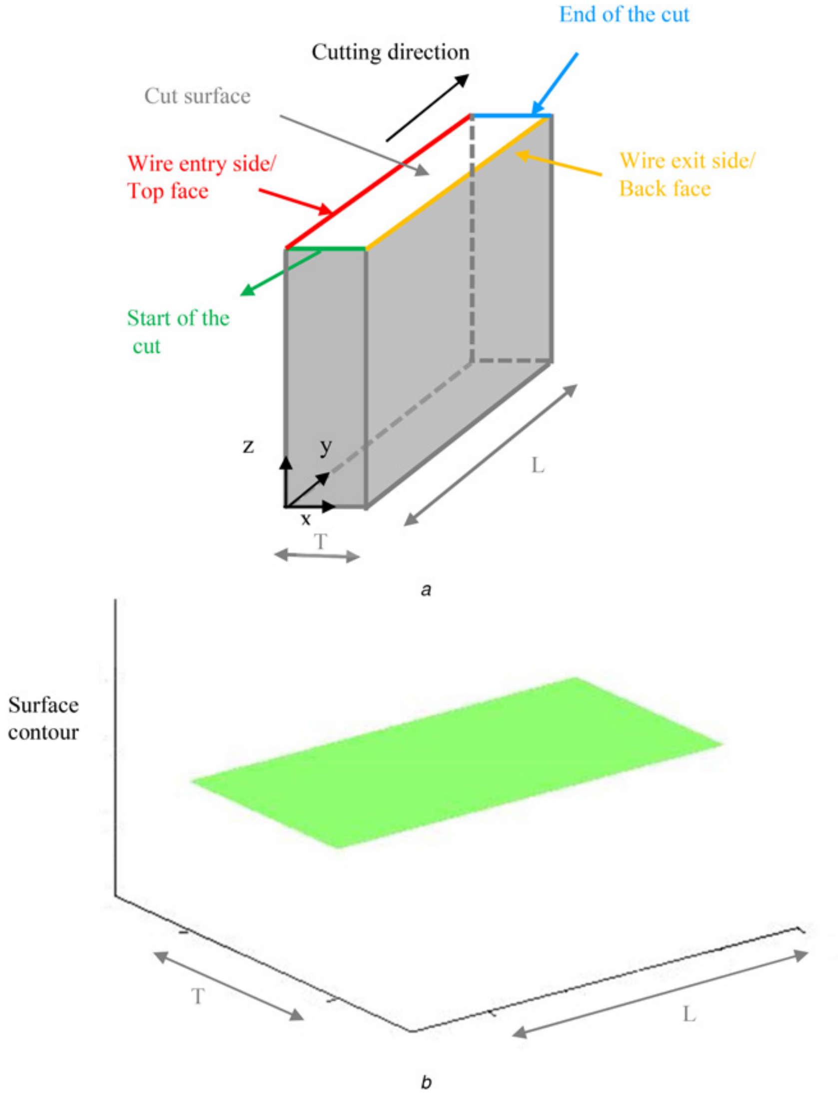

Fig. 3 *Schematic drawing for a typical cut part*
a Schematic drawing of a cut part showing the cut surface, direction of the cut, wire entry and exit sides, start and end of the cut
b Schematic drawing of an ideal flat cut surface in the absence of residual stress

what practical steps can be taken to control the cutting process, see later.

The initial internal stress state of the body can influence errors arising from conditions (a), (b) and (d). For example, the body may distort during cutting and affect (a), and for this reason rigid clamping of the test component is recommended. Violation of condition (b) can cause 'bulging errors' [19] which will depend on the elastic strain field at the cut tip. This effect can be mitigated to some extent by restraining the 'mode I' opening of cut surfaces during cutting and a correction procedure can be applied [19]. The last condition, avoiding plastic deformation, is a requirement common to all mechanical strain relief techniques. In a contour cut, plasticity at the cut tip region may occur owing to redistribution of residual stresses from the cut face where the stresses have been relieved. The degree of error for condition (d) is highly dependent on the stress state in the stressed body, the restraint conditions and the cutting strategy

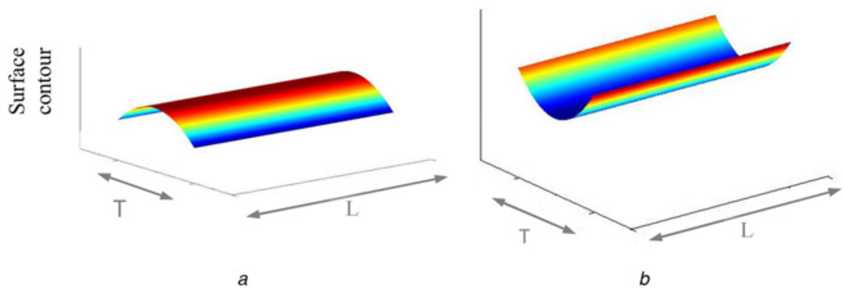

Fig. 4 *Schematic drawing of*
a Convex
b Concave surface cutting artefact for a stress-free test specimen

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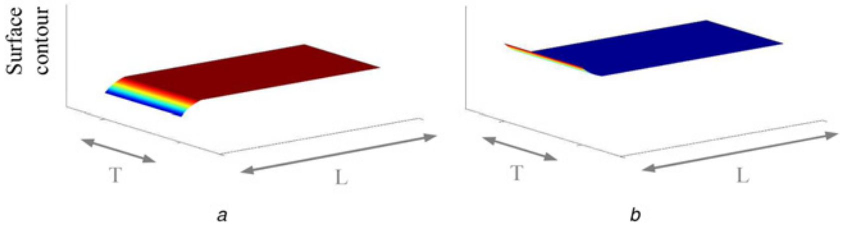

Fig. 5 *Schematic drawing of a cutting artefact at the start of the cut for a stress-free test specimen*
a Contours are low
b Contours are high

[20]. How to control stress relaxation in contour measurement is discussed later in this paper.

3 How to control the contour cut?

Wire electric discharge machining (WEDM) is currently the best method for cutting metallic components for contour method residual stress measurements. Unlike conventional machining processes that require high cutting forces for material removal, WEDM is a non-contact technique that uses an electrically charged thin moving wire where the energy contained in a spark is used to remove (erode) material. The 'finishing' or 'skim' mode of WEDM cutting is preferred for contour cuts because of the lower roughness this setting produces. In addition, the relatively low electrical energy of this mode restricts the depth of any changes in material properties or residual stress caused by the WEDM process to a few tens of microns, and this is considered to be negligible in the context of contour measurements [21].

A schematic drawing of a test specimen that is being cut by WEDM is shown in Fig. 2 to explain the terminology used throughout this paper. The electrically energised wire runs from the top to bottom pulleys at high velocity (~0.1 ms^{-1}) and, as metal is removed, simultaneously traverses slowly in the $+y$-direction to cut the specimen (see Fig. 2*a*).

When referring to the cut surfaces (and associated measured surface deformation data) the following terms are used:

- *Start of the cut:* Refers to the location where the wire begins to cut the specimen (Fig. 2*b*). The smallest y value in the deformation data set will be found somewhere along the line of the start of the cut.
- *End of the cut:* Defined as where the cut is completed, the body is sectioned in two parts and the wire leaves the sample (Fig. 2*b*). The largest y value in the deformation data will be found somewhere along the line of the end of the cut.
- *Wire contact length:* Refers to the length of the portion of wire enclosed by the specimen during cutting. In Fig. 2, 'wire contact length' is 'T', the thickness of the specimen.
- *Wire entry:* Refers to the top face of the specimen where the running wire enters the test specimen in the $+x$-direction (Figs. 2*a* and *b*). The smallest x value in the deformation data set will be found somewhere along the line of the cut on the top face of the specimen. Note that this is normal to the cut advance direction.
- *Wire exit:* Relates to the back face of the specimen where the running wire leaves the test specimen in the $+x$-direction (Figs. 2*a* and *b*). The largest x value in the data set will be found somewhere along the line of the cut on the back face of the specimen. Note that this is normal to the cut advance direction.

Making a WEDM cut for the contour method differs from normal WEDM machining practice where a roughing cut is followed by several 'skim' cuts in order to achieve close precision and low surface roughness. For the contour method, it is essential to make only a single cut to divide the component into two parts, since subsequent passes would erase the deformed contours of the cut surfaces – the information from which the residual stresses are calculated.

Ideally the cut for a contour measurement in a stress-free body should reproduce the defined surface profile perfectly and the two parts should match exactly, for example, a cut along a plane in a stress-free body should produce two perfectly flat mating surfaces. Any deviating feature found on the topography of such stress-free cut surfaces can be categorised as a 'cutting artefact'. The WEDM process produces surfaces with an underlying level of roughness which can be quantified by various parameters [22] and this imposes a fundamental limit on the residual stress length-scale resolution of the contour method [23]. However, WEDM can also introduce discontinuities associated with wire breakage and cutting instabilities (ledges), transient effects at the start and end of the cut, flared edges (wire entry/exit artefacts), surface bowing, surface waviness and deposition of 'crud' [15, 19, 24].

Fig. 3*a* is a schematic drawing for a typical cut part and shows the dimensions (T and L) and terminology used to identify the different edges of the cut surface (start and end of the cut, wire entry and exit side). An example of a perfectly flat WEDM cut surface on a stress-free test specimen is shown in Fig. 3*b*. Schematic sketches illustrating several types of artefacts that have been observed on WEDM cut surfaces of stress-free test specimens are shown in Figs. 4–9.

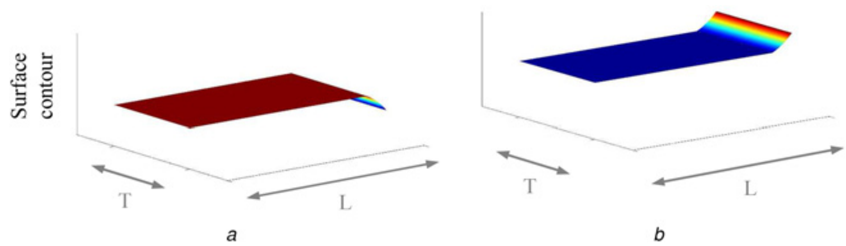

Fig. 6 *Schematic drawing of a cutting artefact at the end of the cut for a stress-free test specimen*
a Contours are low
b Contours are high

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doi: 10.1049/joe.2014.0134

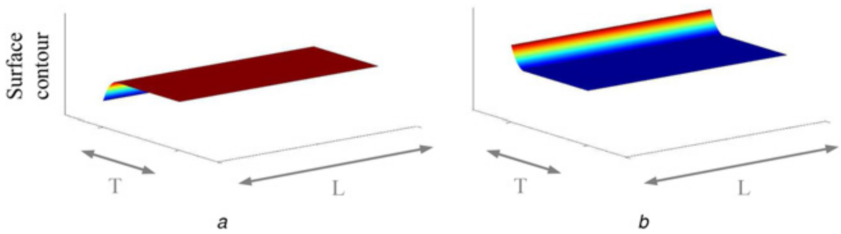

Fig. 7 *Schematic drawing of a wire entry cutting artefact for a stress-free test specimen*
a Contours are low
b Contours are high

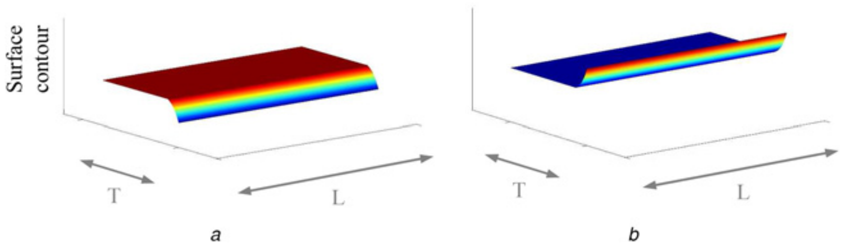

Fig. 8 *Schematic drawing of a wire exit cutting artefact for a stress-free test specimen*
a Contours are low
b Contours are high

The colours in the figures have been selected for a better visualisation of the artefacts, and for the sake of simplicity the surface roughness on the cut surfaces is not shown in the figures. An example of wire breakage and the presence of a 'ledge' on the EDM cut surface that is visible by naked eye is shown in Fig. 10.

The effect of the above-mentioned artefacts on the residual stress measurement depends on whether they are symmetric (i.e. the mating surface deformation profiles possess mirror symmetry) or asymmetric [19], as well as the length-scale and magnitude of deformation perturbation [19, 23]. Potential errors from asymmetric cutting artefacts are of less concern because they tend to be cancelled out in the data processing stage where the measured surface contour data of mating surfaces are averaged. In contrast, symmetric cutting artefacts can introduce significant errors because they are not cancelled out and they have the appearance of features resulting from the relief of residual stresses.

The quality of the cut surfaces can be controlled by using a 'good setting' of WEDM cutting parameters. Such settings can be determined (tuned) by undertaking cutting trials on stress-free portions of the same material of the same thickness (often this can be done on the piece to be measured at a location distant from the region of interest), and by drawing on the experience of practitioners making contour cuts [15]. In general, the aim is to produce the best possible surface finish (minimum roughness) and avoid local irregularities, wire breakage and wire vibration.

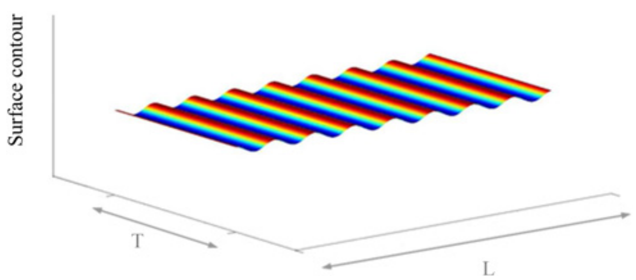

Fig. 9 *Schematic drawing of a surface waviness cutting artefact for a stress-free test specimen*

To identify the key cutting parameters that influence the quality of the cut surfaces, it is necessary to review the WEDM process in more detail. Wire EDM is a thermo-electrical process that erodes the material from the workpiece by using a series of repetitive spark discharges from a pulsed direct-current power supply between the workpiece and the moving wire [25]. The specimen is submerged in a tank containing a dielectric liquid (usually deionised water, but sometimes oil); thus, the workpiece and the wire are separated by a thin film of the liquid. A certain gap between the wire and the workpiece is required to prevent short circuiting.

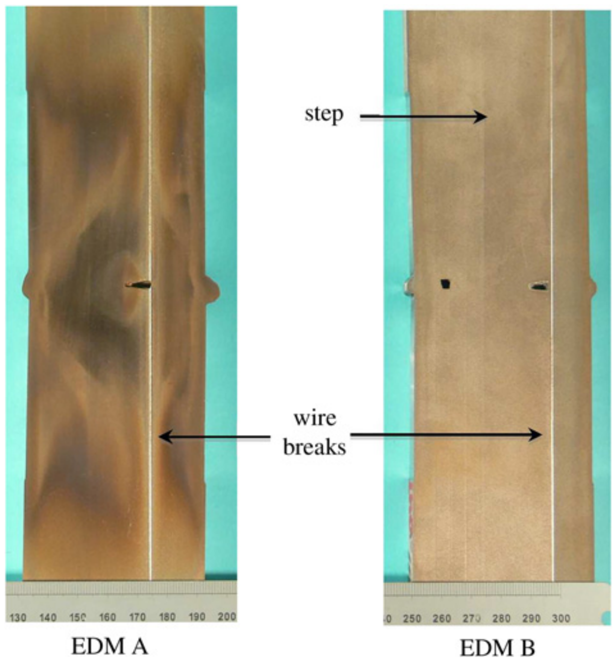

Fig. 10 *Cut surfaces of the 240 mm long × 60 mm deep electron beam welded test components showing weld blow holes and evidence of wire breakages and steps*

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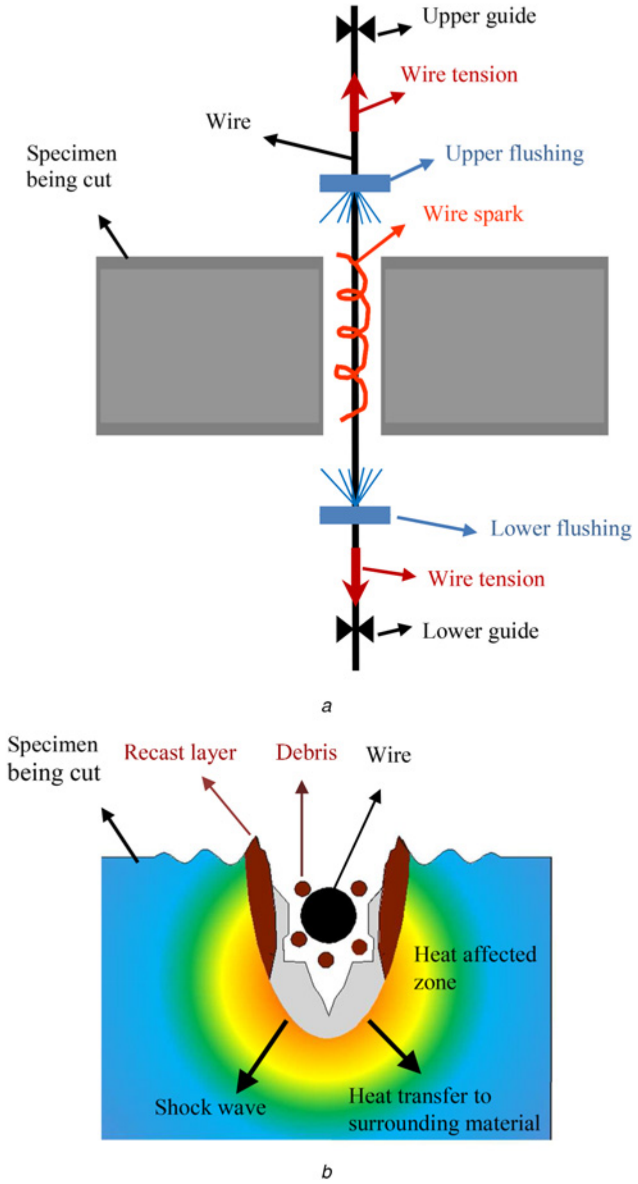

Fig. 11 *Schematic drawing of the EDM process*
a Through-thickness view showing the flushing and WT
b Top view showing the moving wire, debris, re-cast layer and HAZ

This gap should be sufficiently wide to compensate for any vibration of the wire. Electric spark discharge is initiated by a very high voltage that causes breakdown of the resistance of the dielectric in the small gap. The ignition of the spark builds a channel of plasma (ionised electrically conductive gas with high temperature) between the wire and the workpiece that further develops during the period of discharge (discharge on-time). The thermal energy generated in the plasma channel melts some of the material of the wire and the workpiece. At the end of the electrical pulse, when the voltage is removed and the spark is terminated, the temperature of the plasma channel suddenly decreases. The reduction in temperature together with flushing dielectric liquid results in rapid solidification of the evaporated and molten material to form spherical debris particles that are then swept away from the gap. The amount of material removed after each discharge is very small; therefore to achieve a reasonable cutting speed, discharges are made to occur at a high repetition rate [25–27].

The WEDM process is schematically shown in Fig. 11. Normally, the wire is held by a pin guide close to the upper and lower surfaces of the workpiece. Tension is applied to the wire to reduce vibration and deflection which would diminish the quality of the cut surfaces [25].

Surface degradation of the workpiece occurs because of thermal damage from the heat of the spark, see Fig. 11*b*. Surface layers formed on and in the workpiece as a result of WEDM are referred to as the recast layer and the heat affected zone (HAZ) [28, 29]. The recast layer is a layer of molten material and solidified debris that was not completely expelled by dielectric fluid flushing. The HAZ is the portion of the base metal that was not melted during the period of discharge, but whose microstructure and mechanical properties were affected. The thickness of the thermally affected layer depends on the surface temperature distribution during spark pulsation [29]. The thickness of the HAZ is an indication of the depth of residual stresses induced by the thermal cycle of the EDM process [30].

Owing to the many variables involved, the random nature of the erosion process and the interaction of these factors with different materials and geometric configurations, it is not possible (at present) to provide prescriptive guidance on the cutting conditions that will produce cuts closest to the ideal case. Nonetheless, cutting artefacts can be reduced to an acceptably low level by controlling some of the important WEDM variables described below, see also Fig. 12 which illustrates those parameters associated with spark generation.

- *Diameter of the wire:* The diameter of the wire available for WEDM ranges from 0.02 to 0.35 mm.
- *Wire composition:* Plain brass wire is used for most applications, coated wires such as zinc coated brass or coated steel for fast cuts, soft brass for angled WEDM cuts and sometimes tungsten or molybdenum for thin wire cuts [25].
- *Cutting speed:* This is the rate of advance of the wire along the specimen, normally given in units of millimetres/minutes.
- *Wire feed rate:* The speed with which the wire is fed from one spool to the other.
- *On-time:* Discharge duration, Td (A), as described in Fig. 12 [31, 32].
- *Off-time:* Time that there is no current, B, as described in Fig. 12 [31, 32].
- *Short a time:* TAC (i.e. spark rise-time) as illustrated in Fig. 12 is a check by the machine; it backs off or adds extra pulse duration to help to clear restrictions [31, 32].
- *Averaged voltage:* (Aj) Controls the frontal gap (the gap between the wire and the workpiece and controls the straightness of the wire [25, 31, 32].
- *Spark intensity:* (IAL) Mean value of the spark ignition intensity [31].
- *Form of the spark:* (M) As illustrated in Fig. 12, the form of the spark could be rectangular, triangular or trapezoidal.
- *Frequency of the spark:* (FF) Interval between two current pulses, $1/T$ as illustrated in Fig. 12 [31].
- *Injection:* (Inj) Pressure of the flushing dielectric liquid [31].
- *Distance of the injection nozzles to the workpiece:* There are two injection nozzles, one close to the top face (wire entry side) and one close to the bottom face (wire exit side) of the workpiece. The distance between each of the injection nozzles and the workpiece can be adjusted independently.
- *Wire tension (WT):* WT tension is to maintain the straightness of the wire when being subjected to the various mechanical and electromagnetic forces [31].

Note that some of the above definitions, for example, TAC, IAL and FF, may vary depending on the WEDM machine manufacturers.

A summary of the types of cutting artefacts that have been observed together with a commentary identifying possible causes and some potential solutions is presented in Fig. 18 of Appendix.

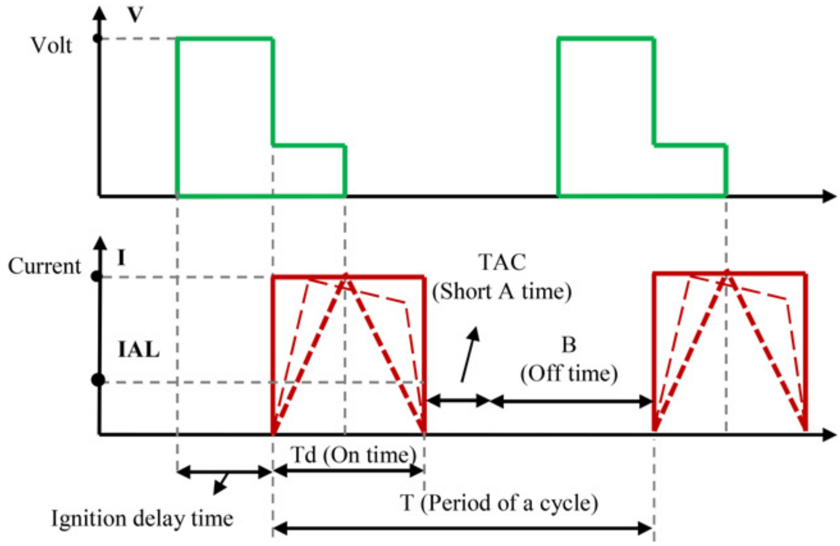

Fig. 12 *Diagram showing the form of the WEDM generated spark together with the trends of the voltage and current [31, 32]*
Note that the indicated definitions are for an AgieCharmilles WEDM machine and may differ for WEDM machines from other suppliers

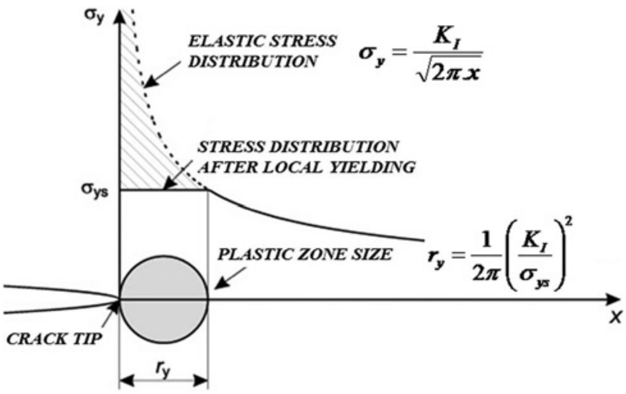

Fig. 13 *Elastic stress distribution ahead of a crack and the corresponding plastic zone generated based on a first-order approximation [33]*

4 How to control stress relaxation?

Like other mechanical strain relief techniques, when high magnitude residual stresses (relative to the material's yield strength) are present in a body, errors in stress measured using the contour method can arise from plastic yielding associated with metal removal. In making the WEDM cut for a contour measurement elastic stress redistribution in the body occurs from the cut face where the stresses have been relieved. This redistribution and the creation of a moving notch at the cut tip create a concentration of stress around the cut tip which may be sufficient to yield the material. To minimise this effect, practitioners of the contour method have recommended that the test component should be clamped securely, close to and symmetrically about, both sides of the cut [19]. Ideally the component needs to be rigidly clamped immediately adjacent to each side of the cut line to prevent any opening or closure of it. However, this is impossible to achieve in practice and a compromise has to be made depending on the size of component and the

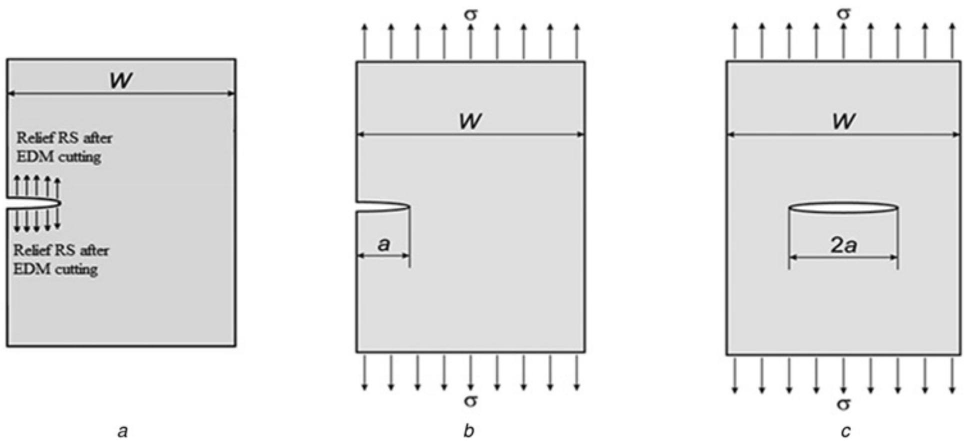

Fig. 14 *Linear elastic fracture mechanics analogy of the residual stress relaxation process in a finite width flat plate*
a Showing wire EDM entry at the edge of the plate [33]
b For an edge crack under remote uniform stress
c For a centre-crack configuration under remote stress
SIF for the embedded crack case (*c*) is much smaller than that for an equivalent edge crack (*b*). The cracked plate example illustrates how plasticity errors in the contour method can be reduced by controlling the cut path to create an embedded 'crack' configuration [20]
W is the plate width and *a* is the crack (wire EDM cut) length

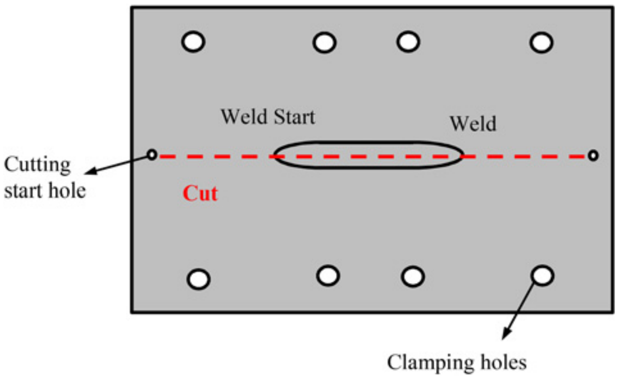

Fig. 15 *Schematic drawing of a 3-pass welded plate showing how an 'embedded crack' contour cut configuration can be created by introducing a cut start-hole in near the edge of the plate [20]*

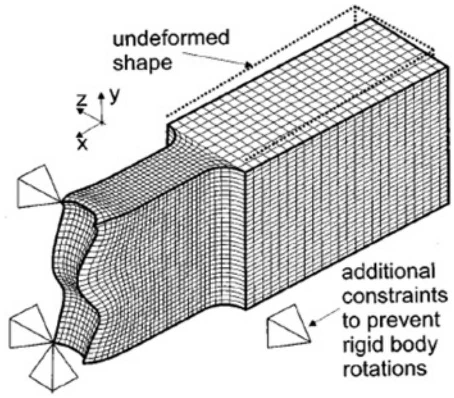

Fig. 17 *Example of a 3D FE model after the measured deformation contour has been applied as displacement boundary condition*
Additional displacement constraints to prevent rigid body motion are also shown [13]

feasibility of introducing holes for fitted bolts or other clamping arrangements. Such restraint configurations must not of course influence the original residual stress field.

Recent research studies have shown that the onset and spatial extent of plasticity along the cut path are dependent on the magnitude of the stress field around the cut as it progresses [19, 20]. This can be assessed using linear elastic fracture mechanics. If the stress field within a body is known, calculation of the mode I stress intensity factor (SIF) [19, 20] as a function of cut length provides a convenient quantitative measure of the susceptibility of a contour cut to plasticity. Indeed the maximum stress at the tip of the EDM notch can be directly related to the SIF and the radius of the notch which is in turn related to the EDM wire diameter. The size of the plastic zone can then be estimated using a first-order approximation [33] for a given cut length in the component being measured, see Fig. 13, and idealised constraint conditions. Furthermore, correlations have been developed linking the average volume of plastically deformed material during a contour cut and the average error in the stress profile measured by the contour method [34].

The general conclusion from this research is that plasticity-induced errors in contour measurements can be mitigated by controlling (reducing) the magnitude of the SIF during cutting. This can be done by choosing an appropriate cutting and restraint strategy. Mode I opening/closure of the cut faces can be restricted by introducing clamping restraint which is closer to the rigid ideal. A different cutting path, such as reversing the cut direction or cutting from the top to bottom of the component or vice versa, may result in SIF profiles having lower peak magnitudes. A novel approach has been proposed [20], in which the SIF is reduced by undertaking an 'embedded cut', that is, using self-restraint of the structure. This can be readily illustrated by comparing the reduced SIF (and crack opening) for an embedded crack in a plate with the SIF for an equivalent edge crack in an unrestrained plate, as illustrated in Fig. 14. The embedded (self-restraint) cutting configuration concept has been applied to a contour residual stress measurement for a 3-pass slot-weld specimen [20] by introducing a wire cutting start-hole, see Fig. 15. In this case, the size of the ligament between the start-hole and the edge of the plate and the configuration of fitted bolts to increase the mode I opening/closure restraint were optimised by undertaking a series of 2D FE stress analyses. The embedded cutting concept has the additional important practical benefit of minimising the need for external restraints and fixturing.

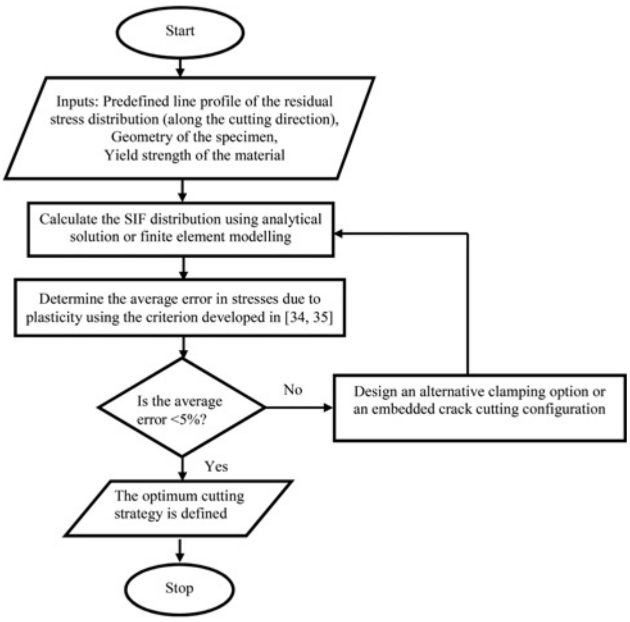

Fig. 16 *Flowchart illustrating a procedure for designing an optimum cutting strategy in order to minimise plasticity-induced errors for contour method residual stress measurement*

A simplified procedure for assessing the likely magnitude of plasticity errors for a selected contour cutting strategy and thereby facilitating design of a cutting plan that can eliminate or reduce plasticity errors is given in Fig. 16. The required input information is the geometry of the test specimen, the yield strength of the material and an estimated residual stress distribution (line profile) along the plane of the cut. A 2D FE linear elastic analysis, analytical solution or weight function method can be used to determine the distribution of the SIF for a defined cutting strategy. Based on the maximum SIF predicted from the FE analysis (or analytical solution), the yield strength of the material and the geometry of the specimen, the criterion developed in [35] can be utilised to assess the averaged error in the contour method stress measurements because of plasticity. Thus, two approaches [34, 35] can be used to estimate when the contour method begins to break down and the levels of error in measured stress that might be expected to arise from plasticity.

5 How to measure the deformed surface?

This section aims to quantify the surface deformation measurement problem that faces the contour method practitioner and develop good practice guidelines for measuring the surface form. To this end, the minimum residual length-scale that can be measured by the contour method is defined, the relationship between the magnitude of the surface displacement, spatial frequency content of the

J Eng 2014
doi: 10.1049/joe.2014.0134

residual stress field and the magnitude of the residual stresses is derived, and the available techniques and their capability for surface contour measurements are reviewed.

5.1 Length-scale

The minimum residual stress length-scale (i.e. wavelength) that can be resolved by the contour method is controlled by the surface roughness of the WEDM cut surfaces [23]. This is turn depends on the wire diameter used and the WEDM cutting conditions. For polycrystalline materials, the grain size is also important as sufficient grains must be sampled to provide a measure of macroscopic residual stresses (Type I) at continuum length-scales. For example, recent investigations on austenitic stainless steel having a grain size of 100 µm and using a cutting wire diameter of 0.25 mm suggest that the minimum theoretical residual stress length-scale over which the contour method can determine residual stresses is of the order of 0.5–1.0 mm [23].

5.2 Residual stress profile resolution

The accuracy to which the contour method can measure a profile of residual stress, acting normal to a cut surface, is fundamentally related to the resolution to which the surface normal displacement contour can be characterised. Through an analytical study, it has been possible to derive a relationship between the magnitude of the surface displacement, the spatial frequency content of the residual stress field and the magnitude of the residual stresses [23]. The significance of the result for engineering components over a range of length-scales (i.e. characteristic dimensions) is illustrated in Table 1. It implies that measurement of usefully detailed residual stresses at the highest spatial frequencies (millimetre length-scale) requires resolution and accuracy of the height data to levels approaching 30 nm. However, the resolution and accuracy requirements reduce as the length-scale of the residual stress field and size of the component increases.

5.3 Surface measurement

Given the sensitivity of the residual stress measurement to the quality of the surface, it is important that components are carefully prepared prior to measurement of surface deformation, for example:

- Ferritic components should be removed from the WEDM bath as soon as possible to minimise the risk of corrosion.
- The cut surfaces of components should be cleaned after WEDM, ideally using an ultrasonic bath.
- Special procedures may need to be developed to remove 'crud' (thin black deposits) from surfaces of some materials after WEDM.
- The deformed component surfaces should be measured in a temperature-controlled room; this should be kept at the same temperature as the WEDM bath if the component has dissimilar materials with differential thermal expansion properties.
- Components should be kept in the metrology room before measurement for long enough to ensure that they have reached the temperature of the room throughout their volume.

Table 1 Relationship between wavelength, peak-to-peak residual stress, and maximum displacement amplitude for a cosine distribution of displacement applied normal to the edge of a semi-infinite plate

Wavelengths, mm	Peak stresses, MPa	Displacement amplitudes, µm
1	±25	±0.034
5	±25	±0.169
10	±25	±0.338
25	±25	±0.845
50	±25	±1.69
100	±25	±3.38
200	±25	±6.76
400	±25	±13.5

The contour method residual stress results are only as good as the degree to which one can measure deviation from planarity of the cut surface. The surface profile may be measured using tactile, optical or electromagnetic methods. The most common techniques for surface contour measurements are reviewed in Table 2 and the capability of each technique and their advantages and disadvantages are explained.

Coordinate measuring machines (CMM) with contact probing systems are most commonly used for contour surface measurements as they are widely available in many workshops and can measure large engineering components with micron level resolution and accuracy. The following guidance is provided to improve the accuracy and reliability of contour measurements made using a CMM contact probing system [23, 36, 37]:

- The stylus system should be as simple as possible: a single straight stylus will generally give better performance than a stylus with bends and joints.
- The stylus is preferred to be short and stiff; the more the stylus bends, the lower the accuracy.
- The stylus tip diameter should be as large as possible for the measurement task. Increasing the tip diameter reduces the effect of the surface finish on the measurement being taken. In effect, a large diameter tip samples the peaks of the surface form over a larger area, and thereby reduces random statistical variations because of the roughness of the surface. The choice of the stylus tip diameter also depends on the residual stress length-scale of interest.
- Owing to the repetitive touch mode used for contour measurements, the stylus may suffer from stiction problems and need to be regularly replaced.
- A special stylus system may be required for magnetic materials.

The electromagnetic category includes the atomic force microscope (AFM). The AFM is not suitable for the application of the contour method to engineering samples because of the very limited working volume and slow speed. It might yet be applied to novel work measuring stresses on a micro-scale.

The optical category includes laser sensors and interferometry. Interferometric techniques include those based on optical flats, and on the moiré fringes between a reference pattern and a projected image on the surface to be measured. They tend to be limited to smaller samples because of the dimensions over which optical planarity can be maintained [38].

The merits of laser sensors are better resolution and accuracy and faster acquisition compared with CMMs. They can gather thousands of data points per second with high accuracy. The fast speed of laser sensors is an advantage for surface contouring of large components compared with the speed of CMM contact probes. With regard to the contour method, laser sensors can provide measurements very close to the edge of the sample, which is of paramount importance where near-surface residual stresses are desired to be determined. However, handling the large data sets these systems produce can be problematic, usually requiring some sort of data reduction process. The finite diameter of the laser beam (typically at least 50 µm) also makes it more difficult to define the perimeters of components accurately.

Other sources of uncertainty in measurement of surfaces are listed in Table 3 together with guidance on how to avoid or reduce them.

Table 2 Summary of the available techniques, their resolution, advantages and disadvantages for surface contour measurements [23, 55–61]

Measurement techniques	Types	Descriptions	Typical resolutions	Advantages	Disadvantages
CMM	tactile (discrete mode)	contact probes have a stylus whose tip makes contact with the workpiece being measured. In discrete point probing, the CMM lifts the probe head from the surface of the workpiece, moves it forward and lowers it until contact is made again, this happens for every data point that is collected	~0.5 µm	• can measure any hard surfaces and there is no limit on the measuring range	• relatively slow and is unsuited to measuring large components • wear of either the probe or the cut surface to be measured • cannot provide measurements close to the edges of a sample; this may be as far as a complete pitch (typically 0.5 mm)
	tactile (scanning mode)	in scanning mode, the probe is brought into contact with the surface of the workpiece and is dragged over it, remaining in contact with the surface for the duration of each scanning cycle		• can measure any hard surfaces and there is no limit on the measuring range • it is faster than the discrete mode of operation	• uncertainty in measurements because of insufficient mechanical stability [23] • wear of either the probe or the cut surface to be measured is more significant than the discrete mode of operation • cannot provide measurements close to the edges of a sample; this may be as far as a complete pitch (typically 0.5 mm)
triangulating laser	non-contact (optical)	it operates with a laser diode illuminating a spot on the surface of the measurement target with visible light. The light reflected from the spot is imaged by an optical system onto a position-sensitive detector and is processed to detect the scattering location. Using simple geometry, the distance of the sample from the probe is calculated and recorded	~0.15 µm for 10 mm measuring range, ~0.03 µm for 2 mm measuring range	• fast speed, in particular for large components • provides measurements very close to the edges of a sample	• problematic on very dark or mirror like surface finishes • there is a trade-off between the maximum resolution and the measuring range of triangulating laser probes
confocal laser	non-contact (optical)	a coherent monochromatic light source illuminates the sample and involves a pinhole in the final stage of optics. The objective lens is coupled to a tuning fork. The rays of light pass through a pinhole before falling on a light sensitive element. The motion of the objective lens causes the quantity of light passing through the pinhole to vary as the sample passes in and out of focus. The location of the focal plane and hence the sample is determined by correlating the point of highest intensity with the motion of the lens	~0.028 µm for 1 mm measuring range	• can measure any surface • a good option for very small samples and where high resolution is required to measure shorter displacement wavelengths	• the range of operation for typical confocal probes is <1 mm. This means that samples need to be aligned very precisely before measurements can be taken, and the movement of the camera head requires very high-precision air bearings. Therefore it is not practical to be used for surface contour measurements of large engineering components

Continued

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doi: 10.1049/joe.2014.0134

Table 2 *Continued*

Measurement techniques	Types	Descriptions	Typical resolutions	Advantages	Disadvantages
interferometry	non-contact (optical)	inside an interferometer objective, the light beam passes through a beam splitter, which simultaneously directs the light to both – the sample surface and an integrated reference mirror. The portion of light that is reflected from both the surface of the sample and the reference mirror recombines into a fringe interference pattern. This pattern provides a measure for the relative vertical position of the observed sample areas and therefore a highly accurate surface information	Few nanometres to sub-nanometres (depending on the objective magnification)	• measuring stresses in micro-scale	• problematic on EDM cut surfaces
confocal imaging microscope	non-contact (optical)	the surface of the sample is scanned vertically in pre-defined steps during which every point on the surface passes through the focus level. All image information that is out of focus is discarded. The acquired confocal images provide detailed 3D information of the surface of the sample	ranging from 2 to 150 nm (depending on the objective magnification)	• measuring stresses in micro-scale	• not suitable for engineering samples because of the very limited working volume and slow speed

6 How to analyse the data?

The measured deformation data defining the cut surface profiles have to be processed into a suitable format before they can be applied as boundary conditions to an FE model to back-calculate the original map of the residual stress. The steps required to analyse the data are as follows [39]:

Aligning: Since the mating cut surfaces are measured in different local coordinate systems, it is necessary to align the measured deformation data sets. This procedure requires translation and rotation of one data set in the *x*–*y*-plane to overlay the other and can be facilitated by using the measured perimeter of the two cut parts.
Interpolating to a common grid: Owing to uncertainty in the lateral motion of CMMs or the stages that are used to run laser sensors, the alignment of the cut surfaces or the defined local coordinates, the data points of one surface may not be exactly overlaid on those of the other. Therefore for further data processing, it is necessary to linearly interpolate the two sets of data onto a common grid with approximately the same density as the original measured data points.
Extrapolating to the perimeter: In the FE model used for the contour method calculation, the displacements must be applied to all the nodes on the cut surface including those on the perimeter of the cut face. Since accurate measurement of the surface deformations on the outline of the cut surface is often not practical, the measured data points are usually extrapolated to the perimeter of the cut parts.
Averaging: The measured surface data points of both cut surfaces must be averaged at each of the measurement *x*, *y* grid points. The averaging step is essential as it removes several potential sources of error; for example, effects of shear stresses and small imperfections in the measured data because of asymmetric cutting artefacts. The two sets of data, now on a common grid, are averaged point by point to generate a single data set that is used for further data processing.
Cleaning: At this stage, any measurement points that are clearly outliers from the overall surface contour are removed from the data set. Such measurement points might exist because of errors in the surface contour measurement, for example, the CMM probe slipping at the edge of the sample; or because of any localised cutting problems, for example, EDM wire breakage.
Flattening: The reference plane for the measured surface contour is arbitrary. The zero position of the out-of-plane measurement direction is calculated by taking an average of the whole data set, which is effectively placing the zero point in the middle of the data set.
Smoothing: This is the commonly used term that refers to the process of fitting the set of averaged, cleaned and flattened deformation data to an approximating function that captures important patterns in the displacement data while heavily attenuating the noise. The function is then used to determine displacement boundary conditions that are applied to the FE model for the elastic stress analysis. Data smoothing (fitting) is essential as any variations in the surface contour because of the surface roughness of the WEDM cut is amplified by the elastic FE stress analysis. Different fitting methods can be used, for example, 2D spline fitting, Fourier series or polynomial smoothing. It has been reported that the Fourier series method cannot always capture all the important features of a surface contour [39]. Spline fitting is currently the most widely used approach. The data smoothing step is discussed in more detail below.
Evaluating the data for the FE model: The final step of the data analysis is to evaluate the *z*-coordinate of the smoothed data at the *x* and *y* locations of the nodes of the FE model, and reverse the sign of the deformation.

6.1 Data smoothing

Spline fitting has been the most commonly used fitting (smoothing) technique for the data analysis step [14, 15, 17, 40–42]. At the Open University, smoothing has been carried out by curve fitting, using a 3D cubic spline-based algorithm [43]. The algorithm works by

Table 3 Examples of sources of uncertainty, the reasons and how to avoid them for surface contour measurements of the contour method [23, 36, 37]

Source of uncertainties	Reasoning	How to avoid?
temperature effect	for high-precision measurements, a stable temperature is important because of the following reasons: • the accuracy of surface measuring machines (for example CMMs) is guaranteed by the manufacturer at 20°C • changes in temperature affect both the surface contour of the sample to be measured and individual components of the measuring vehicle	conduct surface measurements for the contour method in a temperature-controlled room with at least 'close temperature control' of ±1°C per day and ±0.5°C/h [62]. Prior to cutting allow the clamped test component to reach thermal equilibrium with deionised water in the EDM tank. Similarly, keep the specimen inside the controlled temperature metrology laboratory for a period of time before the measurement is conducted, sufficient to bring the sample into thermal equilibrium with the laboratory environment. This will vary with the sample size and thermal conductivity
surface cleanliness	the sample for measurement must be clean and free from grease, smears, liquids and dust. • any particle on the surface may become part of the measured data and result in error in contour method measurement • debris pickup may occur when using contact probes. This would affect the measured data locally or it may stick to the probe and travel along the surface, affecting height measurements beyond its original location	clean the standard calibration test specimens before each use. When using contact probes, clean the ruby tip of the stylus before each use. Clean the cut parts in ultrasonic bath to ensure the EDM cut surfaces are free from any dirt or particles prior to surface measurements. Maintain the environment of the laboratory in a 'clean' condition
wear problem arising with contact probes	wear of either the probe or the cut surface to be measured is potentially a source of concern when using contact probes. This problem warrants attention especially for the scanning mode of CMM contact probe measurement. When using a ruby probe on steel, it is the ruby that will wear the most. Wear of the ruby tip forms a flat region and results in loss of its sphericity. However, unless this wear appears during the course of the measurement of a single sample surface, its influence on the contour measurements is unlikely to be very significant	inspect the probe tip regularly and change the probe tip when a flattening is noted. suggest a preferred strategy for the order in which the height measurements are taken. If a large, hard and rough surface (i.e. one that is likely to wear the tip) is being measured, it is preferable to build up measured areas by scanning along the smallest dimension most frequently, such that the number of contacts between probe tip and sample are minimised between any given measurement and all its nearest neighbours
scanning mode of operation with CMM contact probe	recent experience at the Open University has demonstrated that significant outliers near the edge of surface contours appear when using the scanning mode of operation with the CMM contact probe. This result is consistent with the fact that when CMM is used in scanning mode, the readings are taken from the probe while the frame is in motion, and the system is not sufficiently mechanically stable to provide reliable height data, resulting in the extreme and frequent outliers we have observed	use the CMM contact probe in discrete mode; it performs better than the scanning mode because it waits for the motion to stop before taking a large number of height readings and reporting their average value
probe sticking when using CMM contact probe	when using a CMM with the contact probe in discrete mode to measure surface contours of large samples, it may sometimes happen that the CMM suddenly stops. This may be because of the probe sticking. When performing repetitive measurements, the spring-loaded mechanism inside the probe sometimes will not quite return to the neutral position when not in contact with the sample. The switch then remains open, and the CMM will stop because of a conflict between what it expects and what it measures	replace the probe module regularly

joining the polynomial pieces used to form the spline at regular intervals known as knots. The knot spacing is then adjusted to allow the best fit to the data, with fitting carried out using least-squares analysis. Too small a knot spacing tends to over-fit the data, resulting in the surface roughness being incorporated into the final smoothed surface contour, whereas using too large a knot spacing results in over-smoothing of the underlying surface contour required for accurate calculation of the full field residual stress, and a loss of spatial resolution in areas of rapidly changing stress.

Conventionally, the optimum smoothing parameters, for example, the knot spacing, is determined by subjective judgment, making comparisons between smoothed data and originally measured surface data along a number of line profiles [44–46].

However, when rigorous measurements are of paramount concern, optimal smoothing can be achieved using a more objective method. This approach involves incrementally refining the knot spacings and calculating the stresses for each increment [39]. The uncertainty in the calculated stress at a given node is then estimated by taking the standard deviation of the new stress at each increment from the stress at the previous increment having a coarser knot spacing. Finally, an averaged uncertainty over the whole stress map is calculated by the root mean square of all the nodal uncertainties. The optimum smoothing is then achieved by minimising uncertainty in the calculated stresses [39].

6.2 Stress calculation

For the stress calculation (step C of the contour method, see Fig. 1) a 3D FE model of one half of the workpiece is created. Since the measured deformations because of stress relaxation are very small

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doi: 10.1049/joe.2014.0134

compared with the dimensions of engineering components and the stress analysis is elastic, for convenience, the cut part is modelled in an undeformed state (having a flat cut surface) [13]. The FE model is then meshed and the elastic isotropic material properties (Young's modulus and Poisson's ratio) are input. The displacements derived from the smoothing function fitted to the measured surface data are applied as boundary conditions on the FE nodes of the modelled cut surface, with reverse sign. Three additional displacement constraints are required to prevent rigid body motion (see Fig. 17) [13]. Linear elastic stress analysis is then performed to calculate the residual stresses acting normal to the cut surface.

It is important that a sufficient length of the component, that is the dimension normal to the cut face, is modelled. As a rule of thumb, the length must be greater than the largest dimension of the cut face to avoid introducing significant errors in computed stress. This is based on the 'die-away' length for a cosine distribution of stress applied to the edge of a semi-infinite plate [47]. The maximum stress at a distance of one wavelength is 1.4% of the applied maximum and at a distance of 1.5 × wavelength the stress is <0.1% of the maximum.

It is of interest to estimate the effective gauge size of the contour method. This is dependent on the size of the regular grid of deformation measurements, the method used to smooth the deformation data and the type and size of the elements employed in the FE stress analysis. The deformation grid spacing defines an absolute gauge area as each point measurement represents an average height over the area local to that point. The smoothing method applied to the measured surface contours provides another length-scale. For example, if cubic spline fitting is used, the cubic function has three roots and the cubic spline fitted to deformation data points may have up to three turning points. If first-order elements are used for the stress analysis, these have linear shape functions (displacement fields are approximated by straight lines or flat planes) and provide uniform stress results at central Gauss points (i.e. the stresses predicted are values that are constant across the element). Thus if first-order elements are used, the element size used at the cut surface conveniently gives another measure of the gauge size. To represent a generalised cubic spline displacement function (to capture up to three turning points), a minimum of four linear elements are required.

Examples are given below illustrating how the effective 'top-hat' gauge size for contour method measurements can be inferred for cubic spline data smoothing and first-order elements in the FE stress analysis:

- About 0.5 mm grid spacing, 1 mm element size, 5 mm knot spacing: gauge size is 1 mm (limited by FE mesh).
- About 0.5 mm grid spacing, 1 mm element size, 3 mm knot spacing: gauge size is in range 1–3 mm (may be limited by knot spacing as insufficient element density).
- About 0.5 mm grid spacing, 0.25 mm element size, 1 mm knot spacing: gauge size is 0.5 mm (limited by grid).

This gives a rule of thumb that the element size must be less than one quarter of the knot spacing.

7 Conclusions

The contour method is an attractive technique for measuring residual stress in engineering components because it is simple to apply, it uses standard workshop equipment and it gives a 2D map of residual stresses acting in a direction normal to a plane or surface of interest. Controlling the quality of the cut for contour method measurements is crucial to obtain high-accuracy residual stress results. Some commonly observed cutting artefacts have been identified, important cutting parameters identified and solutions for improving the quality of cuts proposed. The second most important factor affecting the accuracy of stress measurements is control of plasticity during a contour cut. This can be achieved by applying fracture mechanics concepts, that is, by minimising the stress concentration at the tip of the WEDM cut. Various sources of uncertainty associated with measuring the surface deformation of cut components have been reviewed and guidance provided on how to achieve the best results. Good practice guidelines for contour residual stress measurement are highlighted throughout the text with more detailed observations and advice summarised in supporting tables provided in Appendix.

8 Acknowledgments

The authors would like to acknowledge the contributions of staff at The Open University including Peter Ledgard, Damian Flack and Stan Hiller. The research has been funded from the UK East Midlands Development Agency, Rolls-Royce Power Engineering Ltd., Lloyds Register Foundation and The Open University. Lloyd's Register Foundation supports the advancement of engineering-related education, and funds research and development that enhances safety of life at sea, on land and in the air.

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10 Appendix

See Fig. 18.

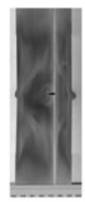
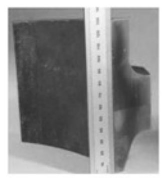
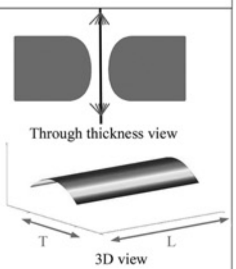
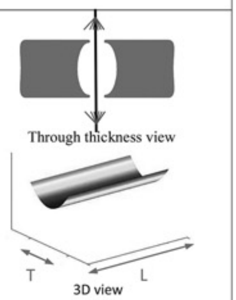
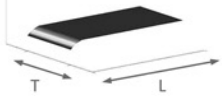
Features	Description	Possible causes	Potential solutions	Illustration
High surface roughness	Surface roughness is a measure of the texture of a surface and is quantified by the vertical deviations of a real surface from its ideal form. Ra is the most commonly used measure of roughness. It is the arithmetic mean of the departure profile from the mean line of the surface.	• Long pulse duration • High spark intensity • Small frontal gap • Inefficient flushing • Mode of the spark A long pulse duration and high spark intensity leads to greater electric discharge energy which will produce a bigger crater resulting in rougher surfaces [25,30,48-50]. A small frontal gap and inefficient flushing does not allow the particles and debris to be flushed away [28,50,51]. The mode of the spark also determines the amount of generated power. For an identical duration time a triangular spark form results in less surface roughness and a trapezoidal spark form results in a rougher cut surface [32].	Control the frontal gap Use a smaller wire diameter [52] Decrease: the on-time and spark intensity Increase: the off-time and flushing Use a triangular spark form [32].	
Wire breakage	Breakage of the wire during the cutting process.	• Large wire tension • High discharge energy • Poor flushing The thermal heat produced during the WEDM process is partly transferred to the wire and is partly lost to the flushing liquid. The generated thermal load is directly linked to the energy of the spark and if it exceeds a certain limit, depending on the thermal-mechanical properties of the wire, the wire will break [27,53].	Decrease wire tension Increase flushing Decrease pulse on-time Decrease spark intensity Decrease the voltage discharge.	
Steps	Steps on the surface at changes in specimen geometry.	• Wire instability The default settings of wire EDM cutting parameters are based on cutting a uniform thickness of a workpiece (constant wire contact length). However, when a cut is conducted on complex geometries for example, cutting a tube along a radial-hoop plane the wire contact length progressively varies along the cutting direction or when cutting a sample having a sharp change in the cross-section the wire contact length changes rapidly at the change in geometry. Change in the wire contact length can result in instability of the cutting condition.	Create a uniform cross section along the cut plane by adding sacrificial material [15], for example using a low melting point alloy.	
Convex cut surface	Through-thickness view of the cut surface is not flat, the cut width through the thickness is not uniform in that more material is removed close to the top and bottom faces (convex from).	• Wire vibration During individual sparks several forces are applied along and upon the wire. The sources of forces are from gas bubbles formed by the plasma of the erosion mechanism, flushing, electrostatic force and electrodynamic force and from debris. These forces result in wire vibration together with wire bending. The nature of the spark is significantly random, hence, the magnitudes and direction of the forces acting along and upon the wire are considerably variable [54].	Increase wire tension Increase averaged voltage Note that increasing the wire tension results in more risk of wire breakage.	
Concave cut surface	Through-thickness view of the cut surface is not flat, the cut width through the thickness is not uniform in that more material is removed at the mid-thickness (concave form) .	• Poor flushing • Wire vibration When the flushing is poor debris is not removed away properly. Flushing from the top and the bottom moves the debris towards centre and results in more sparks (over sparking) in the middle and hence more material removal [32]. For wire vibration see the description of possible causes for the convex cut surface.	Increase flushing Increase averaged voltage Increase wire tension.	
Start and end of cut artefacts	The width of the cut is not uniform at the start/end of the cut, see Figure 2 for the definition of the start and end of the cut.	• Flushing When the wire approaches the specimen (to start cutting) or is about to leave the specimen (to finish the cut) flushing is non-uniform owing to the finite diameter of the injection flushing nozzles. This can cause wire vibration. The effect appears to be more significant at the start of the cut than at the end of the cut. Only when the cut has progressed a few millimetres into the sample does the flushing become more stable and the start-of-cut artefact diminish.	Use 10 mm long sacrificial layer at the start and end of the cut to eliminate this effect [15].	3D view of a cutting artefact at the start of the cut, for more examples see Figure 5and Figure 6.

Fig. 18 *Summary of observed cutting artefacts: description, possible causes and potential solutions*

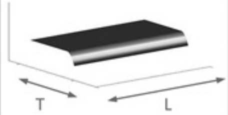
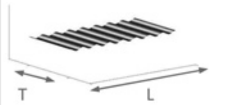
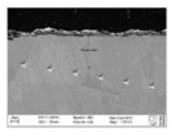
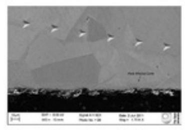
Features	Description	Possible causes	Potential solutions	Illustration
Wire entry/exit artefact	The through thickness view of the cut surface is not flat in that the width of the cut is not uniform though the thickness changing at the wire entry side (close to the top face of the part) or at the wire exit side (close to the back face of the part), see Figure 2.	• Flushing The top and bottom flushing is the most significant parameter that causes unavoidable wire entry/exit artefacts possibly due to the wire vibration. The presence of a wire entry or wire exit artefact is also possibly dependent on the behaviour of the material that is being cut. For example a wire entry artefact has been observed on stress-free ferritic and stainless steel specimen cutting trials whereas a wire exit artefact has been observed on stress-free Titanium alloy cutting trials at the Open University.	Use sacrificial layers 5mm thick at the top and bottom faces of the test specimen along the cut plane [15].	 Through thickness view  3D view, for more examples see Figure 7 and Figure 8.
Waviness	Periodic deformation of the cut surface along the cutting direction.	• Wire vibration • Axis of the moving head may not be robust enough This is possibly caused by wire instability along the cutting direction.	Increase wire tension Check the robustness of the moving axis.	 3D view
Recast layer	The recast layer is a result of molten materials that are not completely flushed away from the workpiece surface by dielectric fluid [28,29].	• Poor flushing • High discharge energy High discharge energy results in melting more material from the workpiece. Therefore the number of particles within the frontal gap increases as flushing can partly remove away the debris. This culminates in over sparking and hence a thicker recast layer [28,49].	Decrease on-time Decrease spark intensity Decrease the voltage discharge Increase the flushing.	 SEM image showing the recast layer for a stainless steel stress-free cutting trial.
Heat affected zone (HAZ)	The heat affected zone microstructure and mechanical properties are affected by the rapid heating and cooling of the cutting process [29,30].	• High discharge energy Note that the extent of the heat affected zone also depends on the material properties of the test specimen that is being cut. Recent stress-free cutting trials at the Open University have demonstrated larger HAZ depths for ferritic steel compared with austenitic stainless steel [52].	Decrease on-time Decrease spark intensity Decrease the voltage discharge Decrease the cutting speed [52].	 SEM image showing the HAZ for a stainless steel stress-free cutting trial.

Fig. 18 *Continued*

doi: 10.1049/joe.2014.0134