Non-destructive measurement of weld toe radius using Weld Impression Analysis, Laser Scanning Profiling and Structured Light Projection methods

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Abstract

Significant stress concentrations in welded structures typically arise at crack like defects and at weld toes. The geometry of the weld toe is therefore one of the primary geometrical features that control the fatigue life of welded components. This work is focused on evaluating three non-destructive methods to measure the weld toe radius: Weld Impression Analysis (WIA), Laser Scanning Profiling (LSP) and Structured Light Projection (SLP). Measurements were first done on a reference block with five different radii. The accuracy of the three methods was estimated by comparing the results with those measured by cross sectioning the reference block and then using image analysis to determine the radius. Finally the non-destructive methods were employed to measure the weld toe radius for a corner fillet weld. Results show that all three methods present precise and accurate values when the cross section of the object being measured is circular. For non-circular cross sections such as a weld toe, the measurements are associated with a larger scatter. WIA seems to be a suitable and economical choice when the aim is just finding the radius. However, SLP is a good method to fast obtain a three-dimensional image of the weld profile, which also makes it more suitable for quality control in production.

Keywords: Weld toe, Non-destructive methods, Weld Impression Analysis, Laser Scanning Profiling, Structured Light Projection.

1. Introduction

A large proportion of all engineering structures are manufactured by welding and very often, welds are the only practical means for joining structures which are subjected to dynamic service loads [1]. Factors that control the fatigue life of a weldment include the material, environment, welding method, weld quality, joint type and the geometric profile of the weld [2], [3].

The weld toe is one of the most probable fatigue crack initiation sites due to the local stress concentration caused by abrupt geometrical changes. It is therefore essential to study the effects of the weld profile, especially the weld toe geometry, on fatigue behaviour. [4], [5]. For example, Perović [6] investigated the dependency of the fatigue stress concentration factors on the weld toe radius by using both finite element analysis and the photoelasticity method for various types of welded joints. Results of his work show that by increasing the weld toe radius/plate thickness ratio, the stress concentration factor decreases. However, it was not mentioned how the weld toe radius was measured.

There are several destructive and non-destructive methods for measuring the weld toe radius. Destructive methods are mainly based on cross sectioning and then measuring the radius using optical microscopy and a software for image analysis. Non-destructive methods can be straight forward like using reference blocks, feeler gauges or Weld Impression Analysis (WIA), also known as the plastic replica technique. They can also be more complicated like Structured Light Projection (SLP) and Laser Scanning Profiling (LSP) methods [1], [7]–[13]. Many researchers have applied these techniques to characterise weld geometries. For example, Pang [7] and Engesvik et al. [8] used a sectioning technique to acquire the toe geometry of welded specimens. Alam et al. [1] used the plastic replica technique to measure the local weld geometry, i.e. weld toe radius, weld angle and notch depth for a fillet joint. Stenberg et al. [9] used reference block, feeler gauge and Structured Light Projection to measure the toe radius along the weld bead in a T-joint. Their results show that using reference blocks and feeler gauges do not provide the required accuracy and are subjective when measuring the toe radius. Similar results are obtained when measuring the radius by image analysis software from SLP results. Therefore, based on imported data from the SLP measurements they developed an algorithm that assesses weld bead surface data and automatically identifies and calculates the toe radius in several positions along the weld. Hou [10] used three-dimensional laser scanning technology to obtain the geometry of the weld toe. He processed the scanned result to construct finite element models of the toe to estimate the stress concentration factors along the weld.
Further research to investigate non-destructive measurement methods capturing surface profiles with high resolution and good precision and then measuring the toe radius is needed. The possibility to measure the weld toe radius using three non-destructive methods is therefore evaluated in this paper.

2. Experimental

2.1. Reference block and weld sample

A reference block was machined to have 5 different radii ranging from 0.2 mm to 6 mm as presented in Figure 1. The first three grooves are circular and the last two have V-shaped sides. By using the block as a reference, the accuracy and precision of the non-destructive methods could be estimated. The accuracy of the block itself was determined by sectioning.
The non-destructive methods were employed to measure the weld toe radius for a Gas Metal Arc Welding (GMAW) corner fillet weld. The weld sample and schematic geometrical features of the weld toe are shown in Figure 2.

2.2. Non-destructive methods

2.2.1. Weld Impression Analysis (WIA)

The WIA method combines the impression technique with image analysis. The main steps are:

1. Preparation of impression area.
2. Cleaning impression area with air/water spray and removing excess water.
3. Mixing: Taking equal amounts of the two components (i.e. catalyst and base) using the colour coded measuring spoons and kneading with fingertips until colour of mix is uniform.
4. Apply the prepared putty onto and around the part being measured.
5. Leave the putty for about 2-3 minutes until the impression sets.
6. Remove and then cut the impression revealing the cross section profile of the surface.
7. Place the impression under stereo microscope.
8. Do measurement using image analysis software.

Figure 3 shows application of WIA to the reference block.

2.2.2. Laser Scanning Profiling (LSP)

The Laser Scanning Profiling method uses the principle of optical triangulation. A laser line is projected onto the target surface via a linear optical system. The reflected light from the laser line is received by a CCD element and then evaluated in two dimensions. Apart from the distance information (Z axis), the exact position of each point on the laser line (X axis) is also acquired and received as an output from the system. The radii were calculated based on choosing three points on the X-Z graph using a specially developed Matlab code. The LSP system used for this study was ScanCONTROL from Micro-Epsilon, which is a device with an integrated camera and laser line. Figure 4 illustrates the use of the LSP method for measuring the weld toe radius.

2.2.3. Structured Light Projection (SLP)

The Structured Light Projection method is one of the non-contact techniques that have been used for 3-D shape measurements. A system based on structured light consists of one projection unit and one camera. During the measurement, light patterns with known structures are projected sequentially on the object. At the same time,

images of the object are captured by the camera. Using the triangulation method the 3-D shape of the object is then derived from the images [11].
The vision-system used in this research is MikroCAD and the software for evaluation is ODSCAD. In this software it is possible to define measurement points from which a radius is calculated based on an iteration method. It is also possible to export the measured surface as x-, y-, and z-coordinates into a text file for further data processing. Figure 5 shows the measurement setup of the SLP method used for measuring the weld toe radius.

2.3. Measurements

2.3.1. Measurement of the reference block radii by sectioning

After applying non-destructive methods on the reference block the accuracy of the radii was verified. To achieve this, the reference block was cut along the centre and for each groove the radius was measured using a stereo microscope (Olympus SZX) and image analysis software (Infinity). The radius was measured by using the 3-point command in the software toolbar. The three points are specified by the operator and a circle will be determined which passes through the three points.

2.3.2. Applying non-destructive methods on the reference block

When applying the WIA method to the reference block, three cross sections were cut and then the radii were measured using a low (6.3x) and a high magnification (between 8x to 40x) as shown in figure 3. Table 1 presents the number of tests performed for the three non-destructive methods. In the table WIA-LM and WIA-HM are used for the WIA method for low and high magnification, respectively.
The accuracy and precision of the three methods were then analysed using relative error and standard deviation of measured data.

2.3.3. Applying non-destructive methods on the weld sample

The three non-destructive methods used for the reference block were also applied to the weld sample. For measuring the weld toe radius variation along the weld toe, three cross sections were investigated for each method. Figure 6, obtained by SLP, illustrates the position of the three cross sections. In the figure WM stands for a cross section at the centre of the weld toe and WL and WR are located 4 mm to the left and right of WM, respectively.
It is not an easy task to fit a circle to the weld toe profile. In some cases, it was hard to decide the radius to be measured as either a circle with a local smaller radius or a circle with a much bigger radius could be fitted. Radius measurements were therefore performed in two ways to obtain local (smaller) and general (bigger) radii for each cross section for the SLP and LSP methods. In this study for measuring the local and general radii three points were placed on the obtained profile 1.5 mm and 0.5 mm from each other, respectively. Figure 7 illustrates the WM cross section obtained by the SLP method showing one local and one general circle fitted to it.

3. Results and discussion

3.1. Sectioning of the reference block

After cutting and measuring the grooves in the reference block it was found that the true radii differ from those shown in Figure 1. Figure 8 shows the true shape of each groove. The measured radii of grooves A, B and C are quite close to the expected values but the radii of grooves D and E are not. The true values of the radii are presented in table 2.

3.2. Radius measurements on the reference block

Results of all measurements using the three non-destructive methods and sectioning of the block are presented in table 2. In general, the three different non-destructive methods give similar results when applied to the reference block. All three methods present precise and accurate results for grooves A, B and C. For groove D, the LSP method cannot obtain any measurements because of laser reflections from the V-shaped sides of this groove.
As can be seen in table 2, the highest standard deviation was with groove E with the LSP method. The lowest standard deviation was with WIA-HM.
The highest relative error is related to measuring the radius for groove E using the WIA method while the lowest relative error was for groove A and the SLP method. In general, considering table 2, by decreasing the radius the accuracy decreases and relative error increases. This shows that bigger radii can be measured more accurately than smaller ones. The lack of high accuracy and precision for radius measurements for grooves D and E can be related to their geometry as they don't have circular cross sections. As can be seen in figure 8, the cross section for groove D has V-shaped sides and a flat surface at the bottom and groove E has a semi-elliptical shape.

Considering this, measuring and fitting the circle that best fits the geometry is hard and results in high relative errors and standard deviations.
Comparing the results of WIA-HM and WIA-LM shows that WIA-HM measures the radii with lower standard deviation and relative errors resulting in higher precision and accuracy. A higher magnification picture provides more detail about the cut profile and makes it easier for the operator to define the circle. Use of the WIA method for groove E in figure 3 illustrates this.

3.3. Radius measurements on the weld sample

Figure 9 shows the WM cross section shown in figure 6 obtained by the LSP, SLP and WIA methods. The results of measuring the weld toe radius for all three cross sections in figure 6 are presented in table 3. As can be seen in table 3 the weld toe radius decreases along the weld toe from left to right. A weld toe is usually assumed to have a mathematically perfect and uniform geometry when analysing the weld toe stress and strain [10]. However, as illustrated by the result, the weld toe geometry cannot be considered uniform and its variation along the weld should be considered.
When comparing the local and general radii for LSP and SLP, the general radii are about two times larger than the local ones. For WIA, using the LM and HM approaches, the measured values are almost identical. The LSP-Local, SLP-Local, WIA-HM and WIA-LM methods give very similar results.
Both the quantitative and qualitative characteristics (i.e. weld toe cross section shape, weld surface roughness, etc.) of the weld toe obtained by different methods need to be analysed. Comparing the radius measurement result for the reference block and weld sample, it can be concluded that the measurements for the weld are associated with larger scatter. This can be attributed to the better defined geometry of the grooves in the reference block that makes it easier for the operator to fit a circle and measure the radius. Defining one radius as the weld toe radius for a weld profile is hard and makes it dependent on the operator. Processing the obtained cross sections using image analysis software is another issue resulting in scatter in data. In ODSCAD software the radius can be measured by defining a set of points on which a radius can be measured. Depending on the operator's choice, the program plots a circle. Infinity software used in the WIA method relies on placing three points manually on the profile which a circle passes through and again it depends on the operator. To minimize the influence of the operator, an objective method such as using an automated algorithm for evaluating the weld toe radius would be preferred [9], [11].

3.4. Comparison of non-destructive methods

The SLP method provides a three dimensional picture of the weld toe surface from a single measurement and one can choose a cross section along the weld toe from which a radius can be measured. LSP is a line-scan method which means it is only able to measure points that are in the scanning plane of the laser beam. The WIA method is similar to LSP in that it also requires sectioning if new cross sections should be investigated. With the SLP technique, measurements can be performed much faster than with the other methods. It takes only a few seconds to capture a 3-D picture of the weld profile for further processing. In LSP the measurements of a line-scan can be done in the same time while for WIA capturing the surface profile of a few centimetres takes at least 10 minutes.
In SLP sensors are available for a variety of applications with different measuring areas and resolutions. For example, SLP is also suited for mobile use by hand-held sensors such as the one used in this study. This capability makes SLP ideal for weld inspection of complex and inaccessible parts. Another important issue that should be considered is the data and material storage for later use. In WIA, storage of moulded materials needs special consideration. For example, they should be stored carefully and inadequate storage conditions will shorten the shelf life and may lead to malfunction of the moulded samples. Another drawback of using WIA is that the polymer components used for moulding has an expiry date. For SLP and LSP the results can be stored digitally and can be easily assessed at any time. Data can be exported, for example as a text file and used by other programs such as Matlab. Also the graphics can be exported in different formats for both LSP and SLP.
As mentioned earlier the image analysis software used in SLP is ODSCAD. A useful feature of this software is the possibility of performing profile cuts from the surface in both single and multiple sections. However, the method used for radius measurement needs to be improved for better repeatability. In LSP, there is no special software for measuring the radius and in this study a Matlab code was developed in which a circle is passed through three points selected by the operator from the obtained graph. In WIA, the image analysis software is Infinity that uses a similar solution as LSP.
From a safety point of view the laser light should be used with caution while SLP is eye safe. There is also no reported danger or harm for use of the polymer components in WIA. Two drawbacks for using LSP method, the first also applies to SLP, are the problem with obtaining information from shiny surfaces and secondly, inappropriate laser reflection from geometries that have edges or inclined surfaces such as groove E in this study.

Considering advantages and disadvantages of all three non-destructive methods, SLP is a good choice for radius measurement as well as quality control of weld surfaces where a compact, high precision, fast and 3D measurement method is required. The WIA method is a suitable and economical choice for weld toe measurement when the aim is just finding the radius value from a short weld length.

4. Conclusions

Three non-destructive methods namely Weld Impression Analysis, Laser Scanning Profiling and Structured Light Projection methods were used to measure the radius of grooves in a reference block and a weld toe of a corner fillet weld.

All three methods present precise and accurate results when the cross section of the object being measured is circular. For non-circular cross sections such as a weld toe, the measurements are associated with a larger scatter. This can be related to an easier fitting of a circle to a circular cross section on the one hand and the subjectivity of radius measurement using the image analysis software on the other hand.

WIA seems to be a suitable and an economical choice when the aim is just finding the radius. However, to additionally obtain a three-dimensional image of the weld profile in a short time, SLP seems to be a good method that makes it more suitable for quality control in a production line.

5. Acknowledgements

The financial support of the Swedish Energy Agency is gratefully acknowledged.

6. References

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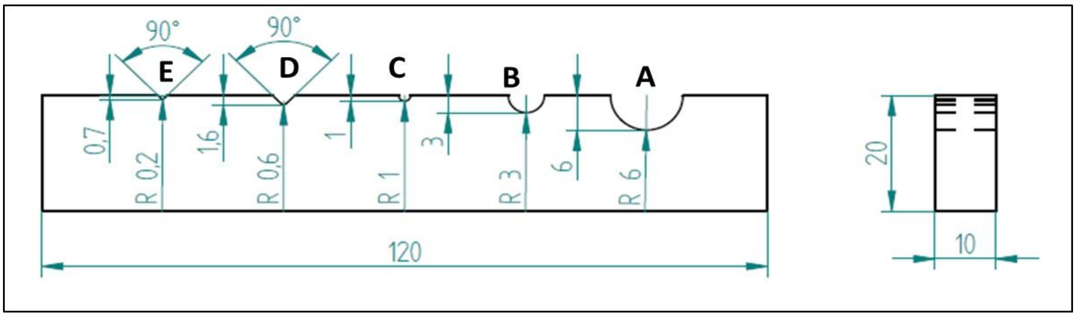

Figure1. Schematic drawing of the reference block.

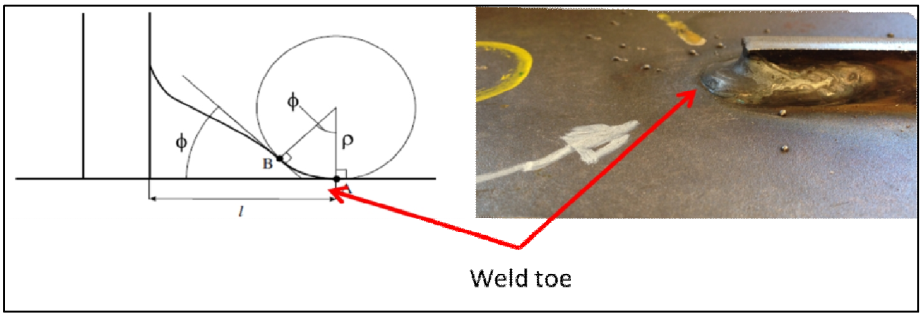

Figure 2. Weld sample with schematic geometrical features at the weld toe.

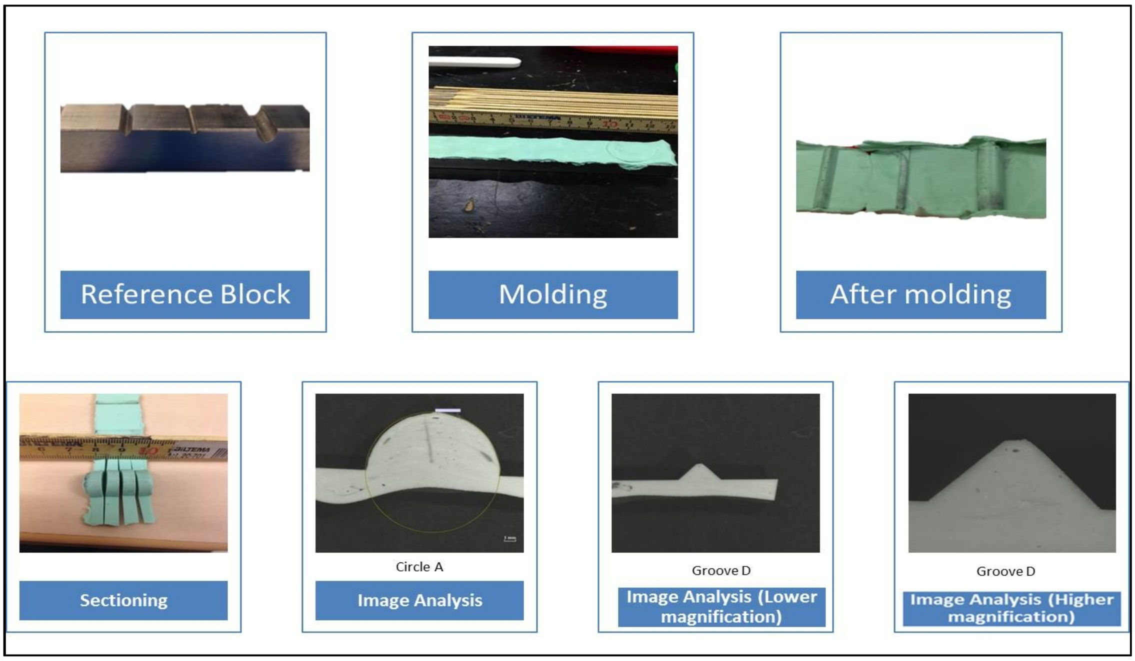

Figure 3. Applying the WIA method to the reference block for the 6 mm (groove A) and the 0.6 mm (groove D) radii.

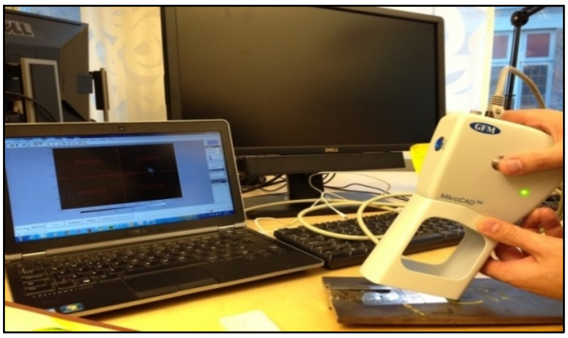

Figure 5. Measurement setup of Structured Light Projection (SLP) method for measuring the weld toe radius.

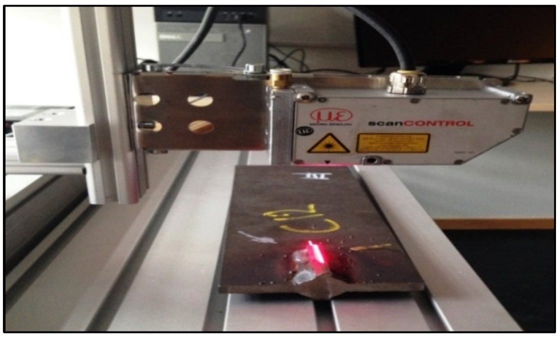

Figure 4. Laser Scanning Profiling method (LSP) for measuring the weld toe radius.

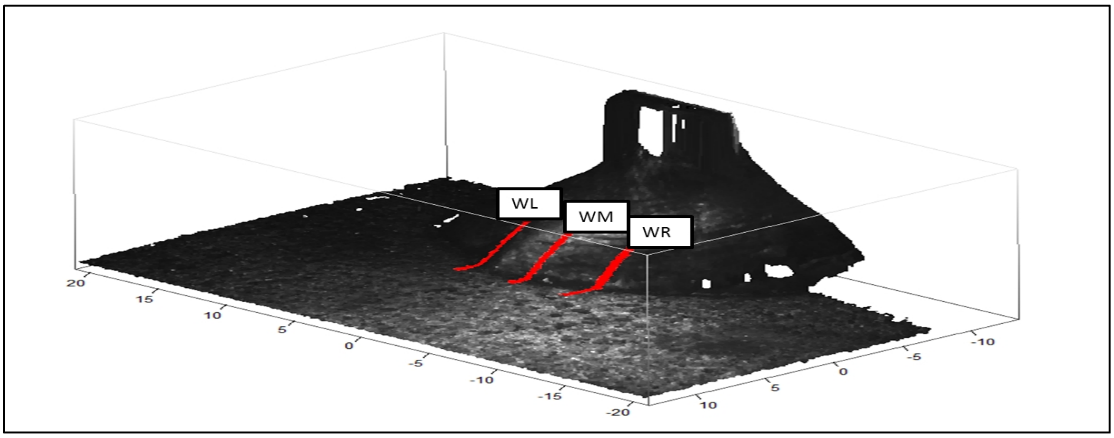

Figure 6. SLP image showing the location of three cross sections used for radius measurement.

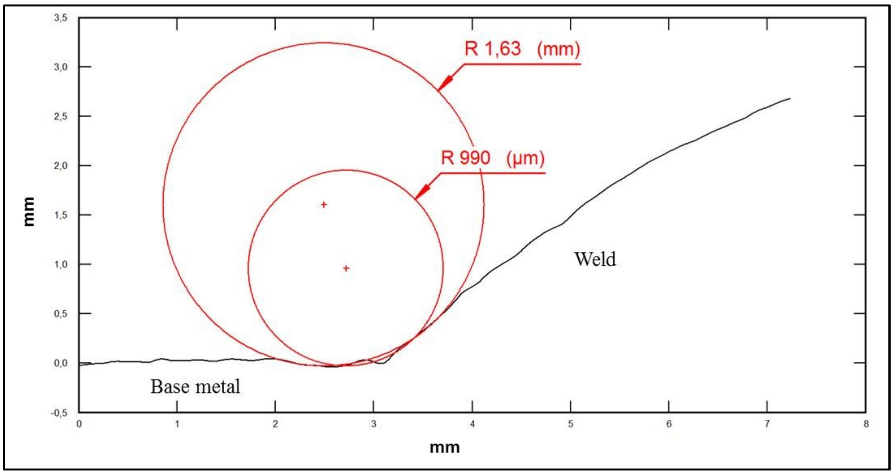

Figure 7. WM cross section obtained by SLP method showing a smaller local and a larger general circle fitted to the profile.

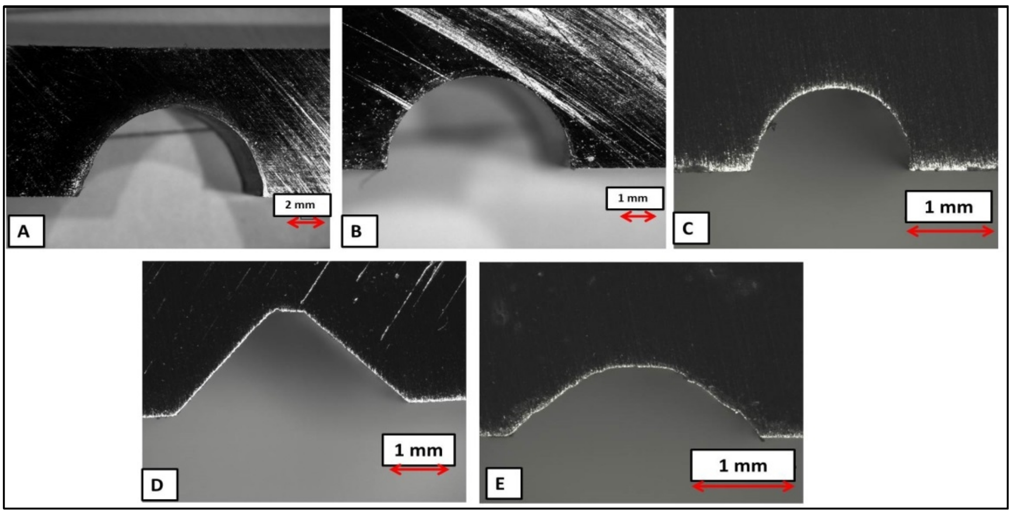

Figure 8. Cross sections of grooves from the reference block after sectioning.

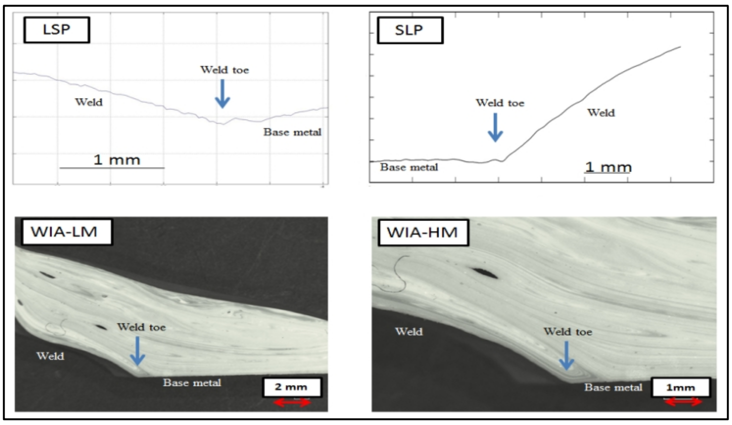

Figure 9. WM cross section for the three non-destructive methods.

Table 1. Measurements used for the reference block.

Method	Number of cross sections investigated	Number of measurement for each cross section
SLP	1	5
LSP	1	5
WIA-LM	3	1
WIA-HM	3	1

Table 2. Result of radius measurements for the reference block using sectioning and non-destructive methods.

	Method	Average (mm)	Standard deviation	Relative error %
Groove A	Sectioning	5.64	0.05	0
	SLP	5.60	0.05	-0.70
	LSP	5.90	0.12	4.57
	WIA-LM	5.74	0.02	1.73
Groove B	Sectioning	2.94	0.04	0
	SLP	2.86	0.01	-2.72
	LSP	3.01	0.02	2.38
	WIA-LM	2.89	0.06	-1.70
	WIA-HM	2.88	0.05	-1.92
Groove C	Sectioning	0.99	0.04	0
	SLP	1.08	0.03	8.83
	LSP	0.98	0.01	-1.00
	WIA-LM	0.95	0.05	-4.62
	WIA-HM	0.97	0	-2.10
Groove D	Sectioning	0.65	0.02	0
	SLP	0.66	0.02	1.53
	LSP*	-	-	-
	WIA-LM	0.61	0.11	-6.15
	WIA-HM	0.60	0.02	-6.66
Groove E	Sectioning	1.15	0	0
	SLP	1.20	0.10	4.7
	LSP	1.26	0.20	9.93
	WIA-LM	0.97	0.16	-15.21
	WIA-HM	1.26	0.16	10.33

*Not applicable because of problems with laser reflections from the V-shaped sides.

Table 3. Weld toe radius results for the three cross sections from figure 6.

Cross section	**Method**		**Weld toe radius (average) mm**
WL	SLP	Local	1.17
		General	2.57
	LSP	Local	1.30
		General	3.01
	WIA	LM	1.14
		HM	1.19
WM	SLP	Local	0.99
		General	1.63
	LSP	Local	0.94
		General	2.60
	WIA	LM	1.15
		HM	1.06
WR	SLP	Local	0.78
		General	1.53
	LSP	Local	0.78
		General	2.46
	WIA	LM	0.90
		HM	0.70