

THE MEASUREMENT OF WELD TOE RADIUS USING THREE NON-DESTRUCTIVE TECHNIQUES

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Abstract: The three non-destructive methods Weld Impression Analysis, Laser Scanning Profiling and Structured Light Projection were employed to measure the weld toe radius of fillet welds. All three methods could be used successfully but results are dependent on evaluation procedure. The results show that the weld toe geometry cannot be considered uniform and varies along the weld. It was also found that the measured weld toe radii do not vary significantly with minor variations of the surface profile orientation.

Keywords: Weld toe radius, Weld Impression Analysis, Laser scanning Profiling, Structured Light Projection.

1. INTRODUCTION

There are many factors that control the fatigue life of a welded component. The geometric profile of the weld is one of the primary factors that influences the fatigue life. Extensive research has studied the effect of weld geometry parameters on fatigue life of welded parts (Singh, et al., 2002; Teng, et al., 2002; Lee, et al., 2009) and it has been found that especially the weld toe radius has a large influence (Caccese, et al., 2006). It is therefore important to be able to measure the weld toe geometry and in particular the weld toe radius.

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 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 (Alam, et al., 2010; Pang, et al., 1993; Engesvik, and Moan, 1983; Stenberg, et al., 2012; Hou, 2007; Peng, 2007; Lee, et al., 2009; Williams, et al., 1971). Many researchers have applied these techniques to characterise weld geometries. For example, Pang (1993) and Engesvik, et al. (1983), used a sectioning technique to acquire the toe geometry of welded specimens. Alam, et al. (2010), used the plastic replica technique to measure the local weld geometry, i.e. weld toe radius and weld angle for a fillet joint. Stenberg et al. (2012), used reference blocks, feeler gauges 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 were obtained when measuring the radius by image analysis software from SLP results. Therefore, they developed an algorithm that assesses weld bead surface data and automatically identifies and calculates the toe radius in several positions along the weld from SLP data. Hou (2007), 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. Barsoum and Jonsson (2011), measured the weld toe radius and flank angle using silicon replicas and a vision system. They conclude that measurement using the vision system is preferable since the radius can be measured along the weld by just one measurement while the replica method provides the radius only where the cut is made through the replica.

In a previous paper (Harati, et al., 2014), three non-destructive methods Weld Impression Analysis (WIA), Laser Scanning Profiling (LSP) and Structured Light Projection (SLP) were employed for radius measurement 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. It was found that all three methods can be used for measuring the radius and they present precise and accurate values. In this paper the focus has been on applying these three methods for measurements of the weld toe radius of fillet welds. Additionally, result were compared by those obtained by sectioning of the welded samples.

2. EXPERIMENTAL PROCEDURE

2.1. Weld samples

Three non-destructive methods were employed to measure the weld toe radius for Gas Metal Arc Welding (GMAW) corner fillet welds. The weld sample and schematic geometrical features of the weld toe are shown in Figure 1.

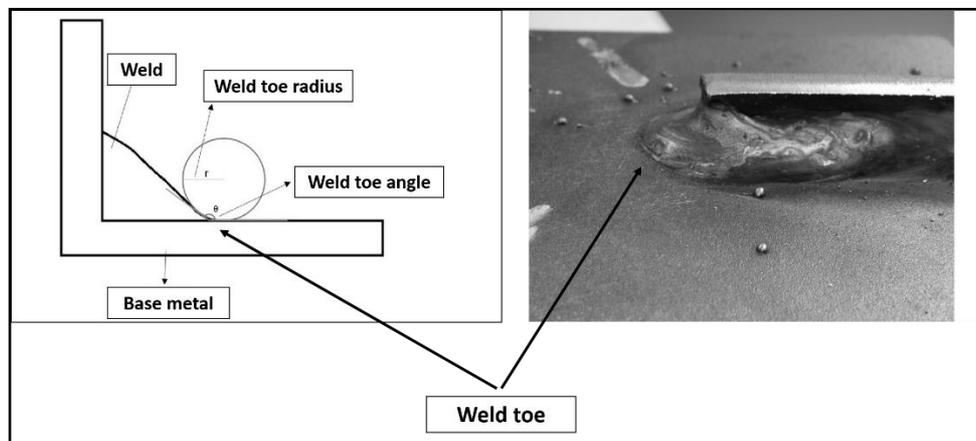


Fig. 1. Weld sample (right) and schematic geometrical features at the weld toe (left).

2.2. Non-destructive methods

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 the catalyst and base.
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.

Two software were used for image analysis: Infinity and AutoCAD. Figure 2 shows application of WIA to the weld sample.

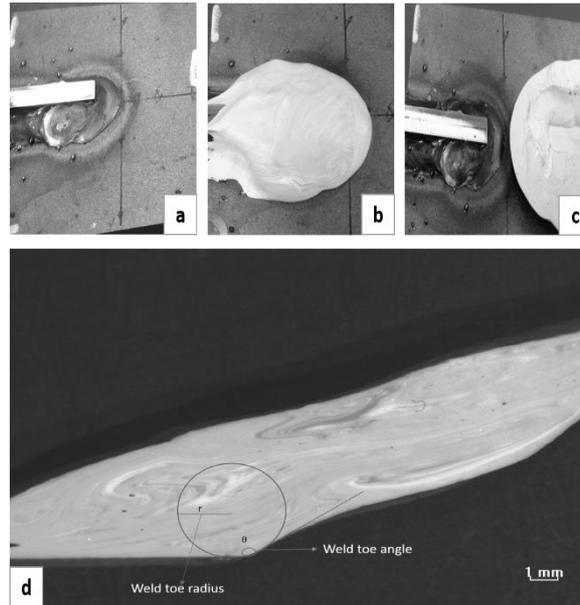


Fig. 2. Applying the WIA method to a corner fillet weld. a) The weld sample before molding b) Applying the putty onto the weld toe c) Weld profile after removing the putty d) Cross section under stereo microscope.

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 are 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 3 illustrates the use of the LSP method for measuring the weld toe radius.

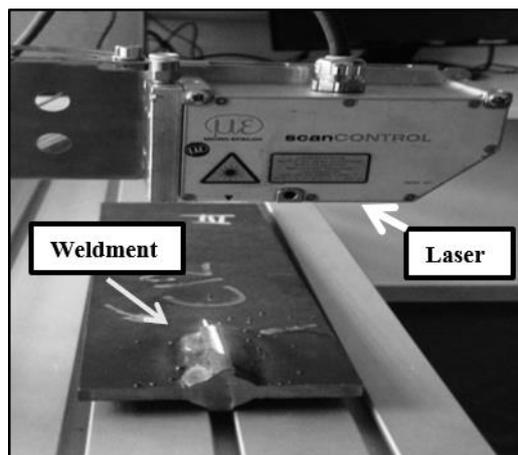


Fig. 3. Laser Scanning Profiling (LSP) for measuring the weld toe radius.

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 (Peng, 2007).

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 4 shows the measurement setup of the SLP method used for measuring the weld toe radius.



Fig. 4. Measurement setup of Structured Light Projection (SLP) method for measuring the weld toe radius.

2.3. Measurements

All three non-destructive methods were used to measure the weld toe radius for the same corner fillet weld. For measuring the weld toe radius variation along the weld toe, three surface profiles were investigated for each method. Figure 5, obtained by SLP, illustrates the position of the three surface profiles. In the figure WM stands for a surface profiles 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 determine 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 equally well. Radius measurements were therefore performed in two ways to obtain local (smaller) and general (bigger) radii for each surface profiles 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.

It is difficult to define with any precision the normal to the intersection with the weld to fusion boundary line. Knowing how the orientation of the surface profile affects the measured weld toe radius is therefore important. To study this effect the ODSCAD software from MikroCAD was employed to apply two different surface profiles for each particular point along the weld toe with different orientations. Figure 6 shows 16 different surface profiles. As can be seen in the figure, each pair of surface profiles of 1 and 10, 2 and 11, 3 and 12, 4 and 13, 7 and 14, 8 and 15, 9 and 16 intersect in one distinct point at the weld toe fusion boundary line.

Additionally, using WIA the weld toe radius was measured at the center of the weld toe for four different corner fillet welds (A, B, C and D). The accuracy of the WIA method was then estimated by comparing the results with those measured by cross sectioning each weld from the same location that was already evaluated by WIA.

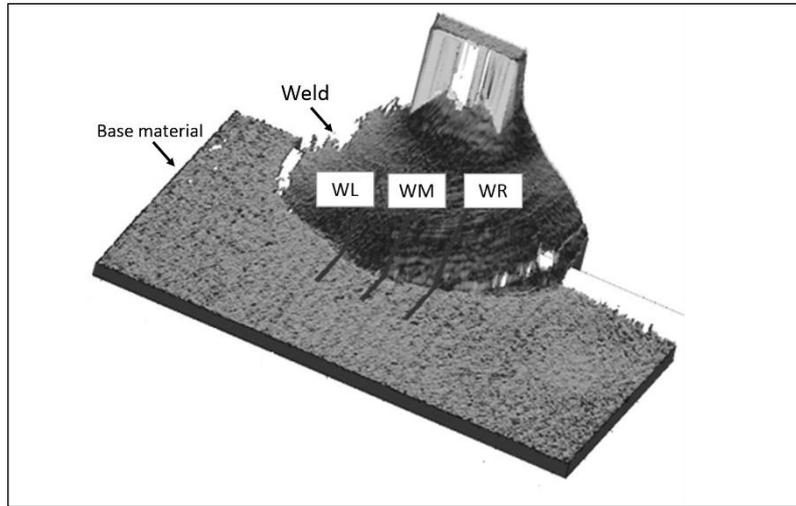


Fig. 5. SLP image showing the location of three surface profiles used for radius measurement.

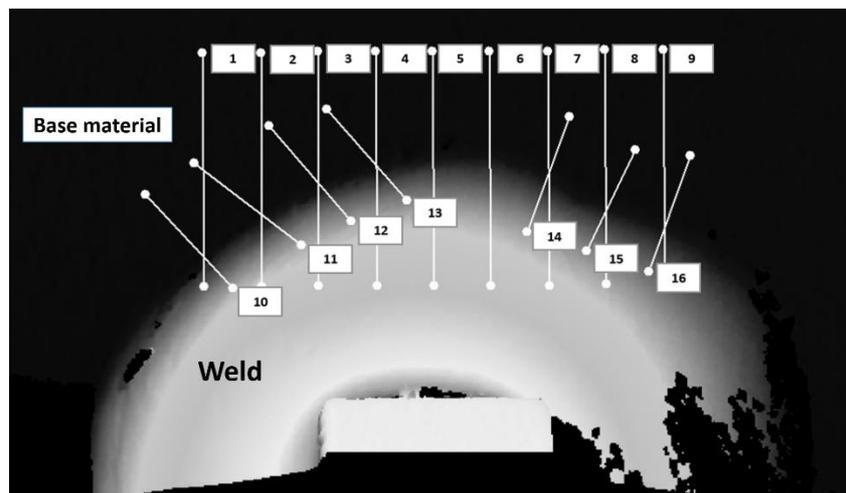


Fig. 6. Top view of the fillet weld in Fig. 5 obtained by SLP method showing the location and orientation of 16 surface profiles used for weld toe radius measurement.

3. RESULTS AND DISCUSSION

3.1. Comparison of WIA, SLP and SLP results

The results of measuring the weld toe radius for the corner fillet weld for the three locations in figure 5 are presented in Table 1. In the table LM and HM for the WIA method refers to low and high magnification, respectively. As can be seen in Table 1 there seems to be a trend that the weld toe radius decreases along the weld toe from left to right but the variation in the measured values is significant. 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 nearly the same. 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 results for the reference block (Harati, et al., 2014) and weld sample in this study, it can be concluded that the

measurements for the weld are associated with larger scatter. This can largely 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 ODESCAD software the radius can be measured by defining a set of points from 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 (Stenberg, et al., 2012; Peng, 2007).

Table 1. Weld toe radius results for the three surface profiles from Fig. 5.

Surface profile	Method		weld toe radius (Average of 5 measurements) (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

3.2. Effects of orientation of measurement line

Table 2 shows the radius measurement results obtained by SLP-General for the 16 different surface profiles in Fig. 6.

Table 2. Weld toe radius results for the 16 surface profiles from Fig. 6.

Surface profile	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Radius (mm)	1.62	1.56	2.25	1.46	1.29	1.64	1.46	1.29	1.64	1.62	1.67	1.92	1.47	1.35	1.27	1.17

As can be seen in the table the weld toe radius varies along the weld toe line. This confirms the results obtained from the surface profiles in Fig. 5. Fig.7 illustrates the difference between the measured weld toe radii using two different surface profile orientations, as shown in figure 6, for each particular point at the weld line. In Fig. 7, surface profiles that intersect in the same point along the weld toe fusion boundary line are grouped in pairs along the horizontal axis and the corresponding weld toe radii are shown on the vertical axis.

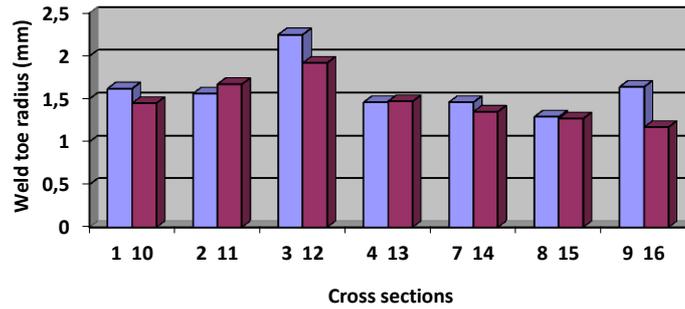


Fig. 7. Comparison of the weld toe radii obtained for pairs of surface profiles intersecting the weld toe fusion boundary lines in the same point but at different angles (see Fig. 6).

As can be seen in the figure the largest measured difference is between surface profiles of 3 and 12 that is 0.33 mm and the lowest one between surface profiles 8 and 15 which is 0.02 mm. Considering results presented in Fig. 7 and table 2 it can be concluded that the difference in the measured weld toe radii when two different surface profiles were used for measuring the weld toe radius in the same point at the weld toe line is small compared to other factors contributing to scatter.

3.3. Comparison of WIA and sectioning results

Table 3 presents the radii for four different corner fillet welds measured by WIA and also by cross sectioning the welds. As can be seen in the table the measured radii after cutting and cross sectioning are similar to those obtained using WIA with one exception.

Table 3. Weld toe radius results for the WIA and sectioning methods.

Weld sample	A	B	C	D
Radius (mm)-WIA	1.70	1.41	1.45	0.62
Radius (mm)-Sectioning	1.33	1.37	2.81	0.78

The radius for weld C measured after sectioning is almost two times bigger than that obtained by WIA. This large difference can most likely be explained by that it is not easy to measure the weld toe radius with both methods in exactly the same point at the weld toe. Changes in location of measurements may result in a big difference in the measured values as the weld toe radius is far from constant as shown earlier.

3.4. Concluding remarks

A comparison of the three non-destructive methods was presented in previously published work (Harati, et al., 2014). Results of the application of these methods to corner fillet welds in this paper confirms the applicability of WIA when the main aim is finding the weld toe radius in one single point at the weld toe line. However, LSP and especially SLP can be better choices when information about variations along the weld toe is needed. Measurements can also be performed much faster with the SLP technique than with the other methods. The software used for radius measurement need to be improved for better repeatability since the measurement procedure in all software is influenced by the judgment of the operator.

4. CONCLUSIONS

Three different non-destructive methods namely Weld Impression Analysis (WIA), Laser scanning Profiling (LSP) and Structured Light Projection (SLP) have been used to measure the weld toe radius for corner fillet welds. The effect of using surface profiles intersecting the weld toe fusion boundary line at different orientations in the same point has also been investigated. Additionally, weld toe radii measurements using the WIA method were compared with results from sectioning of the welded samples.

- All three methods could be used successfully but measured radii are dependent on evaluation procedure.
- The weld toe geometry cannot be considered uniform along the weld.
- The effect of variations of the surface profile orientation relative to the weld toe fusion boundary line is small compared to other factors contributing to scatter.
- WIA is suitable for measuring the weld toe radius when the main aim is finding the weld toe radius in one single point.
- LSP and especially SLP can be better choices when variation of the weld toe along the weld is needed and when time is a factor.

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