Journal of Engineering and Applied Sciences 13 (10): 3444-3449, 2018
ISSN: 1816-949X

Structural Integrity of Welded Joints Subject to Fatigue Loads

[1]Araque de los Rios Oscar and [2]Arzola de la Pena Nelson
[1]Research Group D+TEC, Departament de Ingenieria Mecanica,
Universidad de Ibague, Ibague, Colombia
[2]Research Group OPTIMUN, Departament de Ingenieria Mecanica y Mecatronica,
Universidad Nacional de Colombia, Bogota, Colombia

Abstract: This research presents a theoretical-experimental study about the structural integrity of welded joints under cyclic loads taking into account the influence of initial crack flaws and the cooling rate by the thermal cycle as it relates to this research, steel ASTM A36 HR was the base material and as filler material the electrode E6013 using Shielded Metal Arc Welding (SMAW) as welding procedure. The research topic was approached from an integral perspective, analyzing the behavior of the welded joint from its elaboration phase until its final crack by fatigue with the aim to relate its fatigue life with the experimental factors: load relationship, leg of fillet weld and cooling environment. The welded casting was subjected to an analysis that included the micro-structural and ultrasonic analysis. Also, useful information about the mechanic and fracture-mechanic behavior of the welded joint was gathered throughout tests of axial fatigue and its later monitoring by Scanning Electron Microscope (SEM) in the crack tip and was related with the presence of discontinuities in the welded joint. A high degree of correspondence was reached between the ultrasonic testing and the experimental results.

Key words: Cooling, welding discontinuities, fatigue, structural integrity, ultrasonic, SMAW

INTRODUCTION

The structural welded Joints is one of the most up to date methods at the moment due to the great variety of applications it offers as one of the main in the constructions of structures, pressure devices and machinery. The welded joints show certain types of discontinuities, proper to the process. Most of these welding flaws relate to porosities, lack of penetration and fusion, dross, scours and misalignments, among others. (Maddox, 1994). The size and frequency of the flaws depends on the welding process, the geometry and even the ease of access for welding and the welder's expertise, among other factors. These flaws display a variety of features and in many cases, are difficult and expensive to screen and define without destroying the welded pieces. Generally, the found flaws in the fillet weld are cracks made in the weld roots or fillet weld with internal flaws. A crack is a breakage on the solidified metal. The ASTM E 390 states the cracks on a fillet Weld can be longitudinal, transversal o radially oriented, these can occur in the weld metal, the base metal or on both. The radially-oriented cracks are called crater and are generally originated in the heel fillet. These welding flaws might locally influence in an important manner the stress field around the weld, when the welded component is subjected to variable loads along the time (Alam, 2005).

Flaws in welding: It is likely to detect cracks in the welded joints, once the joint has thermally stabilized. This cracking can be intergranular: along both sides of welded beads. This is produced during the last phase of the solidification weld when the resistance to the compression developed throughout the adjacent grains surpass the resistance of the welded metal, completely solidified.

The welded metal tends to shrink during the solidification by thermal effect. Likewise, the base metal tends to shrink in a low manner due to the fact it does not heat at a high temperature, therefore, the metal shrinking can find an obstacle, especially, if the piece is limited and cannot shrink freely. Therefore, there are some developed stresses in the welded metal during the solidification. The magnitude of this residual stress increases along with the contraction degree, the thickness of the piece and the restrictions that the geometry delivers free contraction to the material.

There are diverse theories about the emergencies of solidification cracks, Singer *et al.* and Borland, incorporate the concept of a solid interlock which is separated by liquid, thin, continuous screens and therefore, separated due to traction stresses such as is presented by Davies *et al.* The fracture surface often has a dendritic morphology, based on a solidification of the welded metal. If some sufficient quantity of

Corresponding Author: Araque de los Rios Oscar, Research Group D+TEC, Departament de Ingenieria Mecanica, Universidad de Ibague, Ibague, Colombia

liquid metal is next to the cracks, the latter can be filled and "healed" the emerging cracks (Kou, 2003).

Cooling in welding: The development of researches about the study of the thermal behavior on welding process has been approached by different researcher like Francis (2001). Zhu and Chao (2002), Araque de los Rios and Arzola de la Pena (2016), among others. The study of thermal behavior shows specific challenges, since this is a transient but no linear due to the movement of the heat source and the dependence of the material properties with temperature as shown by Ramos *et al.* (2007).

Attarha and Sattari-Far (2011) have studied the temperature distribution of both welded joints on the Heat-Affected Zone (HAZ) by using thermocouple "K". The data obtained were compared throughout on Finite Elements Simulation (FEM) 3D, utilizing ABAQUS Software. The experimental and simulation results allow to forecast the temperature distribution on welded shield throughout the tungsten process and Tungsten Inert Gas (TIG). In this study, it was shown that the joining process has a non-linear process, having found a high degree of correlation between experimental results and simulation developed by MEF.

Ultrasonic testing: Ultrasonic testing is based on the measurement of the ultrasonic wave propagation in the respective environment of study. The latter will spread through the material, get reflected, refract and weaken to recognize superficial, sub-superficial and internal flaws on the specimen, be able to measure real thickness, protective films, covering and weld checking. Its purpose uses the acoustic impedance, that is the outcome of maxim speed and density the material has (Mohsin *et al*., 2016; Araque de los Rios and Arzola de la Pena, 2016). On Pulse-echo technique, the energy of sound that is being reflected and is received can be turned in in electric energy, thanks to piezoelectric element owned by the transducer; its main feature is the implementation of the reflected sound portion for the assessment and analysis of flaws, a head plays a double role to be the sender and receiver. This information is displayed on the ultrasonic screen device and can show the pulse amplitude and return duration on the transducer, known as Scan A Rimoldi.

MATERIALS AND METHODS

The experimental analysis of structural integrity is carried out in a test bar with cruciform geometry which were made on ASTM A36 HR steel (8 mm thick) using the SMAW technique for three legs of different sizes. The used device as a warehouse of the welding was Miller XMT 350 CC/CV and electrodes E6013 were used. The specifications for the welding procedure at the moment of storage are shown on Table 1.

Table 1: Specifications for welding procedures

Leg of fillet welding (mm)	Electrode diameter	Electric features (V, A)-CD	Forward speed (mm/min)
3	3/32"	72; 102	20
4	1/8"	69; 92	20
5	1/8"	71,2; 98	20

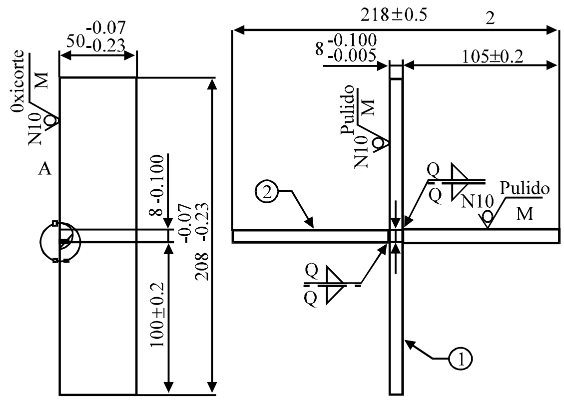


Fig. 1: Geometry of cruciform test piece (unit mm)

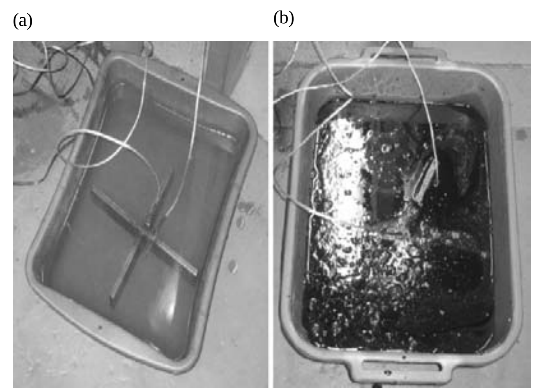


Fig. 2: Cooling process of test pieces: a) Water and b) Oil

The geometry and dimensions of leg of fillet welding are shown on Fig. 1. The Steel plate were cut using the high density plasma technique with a nozzle of 0, 8 mm and the tolerance units for the piece are (-0.23+0.08).

Once the geometry-cruciform test pieces were built, 27 specimens in all, the latter are subjected to a variety of cooling means. Even though the cooling process on oil or water is usual, about the welded joint in the present research, it was decided to study the influence of the post-welding cooling rate as the emergence of different levels of initial flaws, labeled as cracks.

In Fig. 2, the manner the pieces are cooled on water and oil is shown, respectively. The cooling environment consisted of having the test pieces exposed to quiet air, after the welded joint was finished.

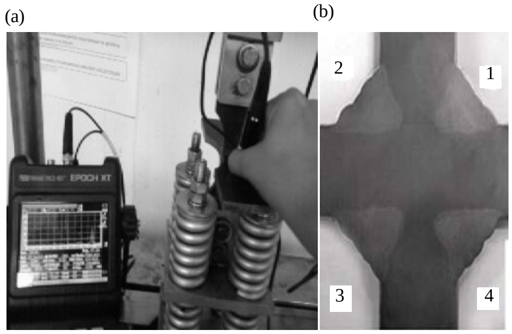


Fig. 3: Testing procedure: a) Ultrasound measurement Scan A and b) Fillet identification on a cruciform test piece

Table 2: Coding in the labeling of cruciform test piece (letter-letter-number)

Digits	Labeling	Values
1st	**Cooling means**	
	A	Water
	B	Oil
	C	Air
2nd	**Leg size**	
	A	5 mm
	B	4 mm
	C	3 mm
3rd	Consecutive number of test pieceswith same number 1-7	

In order to carry out the characterization of the different flaws found on welded joints, an ultrasound device, branded Olympus-Epoch XT was used as well as an a 45° angle probe and 5 MHz frequency. As for the initial testing procedure and sensitivity, a testing device IIW Type 1 was used.

In Fig. 3a, the manner in which the ultrasound testing. On the other hand in Fig. 3b the nomenclature to identify the fillet welded utilized during the testing procedure is indicated.

In order to identify the different test pieces built, according to the experimental arrangement, the aim to identify the different test pieces, based on the cooling means and the dimension of the leg of fillet weld, the coding is made as shown on Table 2.

Once the welded specimens were inspected, they were tested in a axial fatigue, non-standardized device, the fractured surfaces by Scanning Electron Microscope (SEM) using an equipment it marks EDAX with an intensity of 20 keV and backscattered electron.

RESULTS AND DISCUSSION

The utilization of thermocouoples K, inserted in test specimens turned out to be effective for the determination of the cooling curves for the different means. In Figure 4

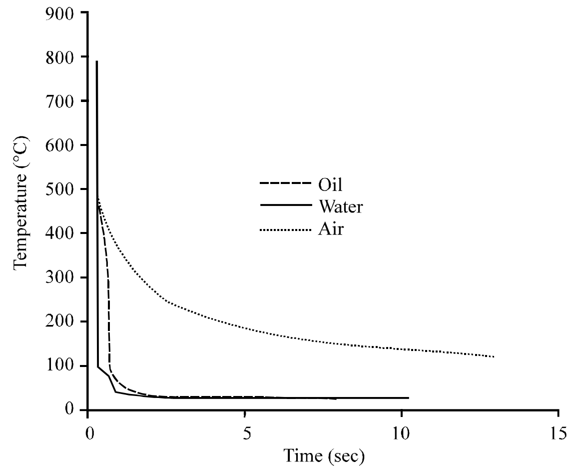


Fig. 4: Cooling curves T vs. Time, for the fillet weld with a side of 5 mm

Table 3: Cooling rate (°C/sec)

	Weld leg size (mm)		
Cooling means	3	4	5
Water	-87, 34	-107, 81	-112, 02
Oil	-62, 42	-66, 70	-70, 90
Air	-8, 426	-8, 83	-8, 97

appears the variation of the temperature measured in function of time for the three cooling means and for a weld side of 5 mm.

As method to determine the cooling rate on straight by minimums squared in the range of temperature registered from the beginning of the measurement up to 200°C. In Table 3 there can be observed the cooling rates, until a temperature t_{final} = 200°C.

It was reached, for example, for a fillet weld side 3 mm, a cooling rate of-87, 34°C/sec when it is cooled in water whereas when it is cooled in still air, the cooling rate is of 8, 42°C/sec until it reaches the same temperature of 200°C. In this way, the experimental design allowed to count on an analysis of order as for cooling intensity of about ten times.

Throughout the ultrasonic inspection, the presence of discontinuities in the set of test specimens are confirmed. These discontinuities in the weld can be determined when observing the behavior of the indications by means of the Scan A technique. It can be indicated that that the ultrasonic beam, corresponding to the flaws: pore and crack both differ between them as for its amplitude and for width. In Table 4, the result of the ultrasonic inspection is shown. There is an indication of the presence of different discontinuities, being considered to be big cracks, those that are bigger than a millimeter in length. In Table 4, there are the following symbols to represent the found flaws found.

Table 4: Flaws found throughout ultrasound inspection

	Face			
Codes	1	2	3	4
AC1	• +		• +	• +
BA6	• θ			θ
BB2				•
AA6		θ +		• +
CB5		θ+	θ+	θ
AA2		•	o+	o+
BA4	o		• θ +	θ
CC1	• θ +	o		
BB1	+	o		+
CC2	θ			θ
CB2		o	θ	
CA4	θ +	θ +	θ	
BB3		• +		
CC5		θ	+	o
AC6	•	+	θ	
CA1			o	o
BC7	θ +	θ	•	
BC2		θ +		
AB6	• θ +	• θ		o
AB5		o+	o	
BC6	o	θ o	• θ	θ
BA3		+		θ
BB5		θ		
CB6		θ		
BA1	θ		θ	θ+
BB1U		+	θ o	θ
BB4			o	

● Initial flaw: big crack; θ Initial flaw: medium-size crack; o Initial flaw: small-size crack; + Circular porosities

It can be inferred that the cracks in the fillet weld are arranged by sizes that range between 100 μm and 1 mm of length. This is typical of cracks of solidification according to indication of ASTM E647 by Wahab and Alam (2004) and Anderson (1994). The size estimation was possible due to the fact that at the moment to carry out the regulation, the calibration of the ultrasound device, the sensibility for the detection of flaws was regulated by an ASTM IIW block, arranged for such an intention.

Later to the identification and characterization of the test specimens, according to the quantity of detected discontinuities using the ultrasound technology, the test of axial fatigue for the all the test specimens. In Fig. 5, the comparative behavior appears between the intensity of existing flaws and fatigue in cycles of load. It can be observed that more intensive cooling means prompt a lenght in less fatigue load cycles, the previous aspect can be a product of the increase of the probability of having more and less of discontinuities, since, they are initial cracks and circular porosities in the weld. These act as initiators of the stable spread cracks, eliminitating the possible initiation.

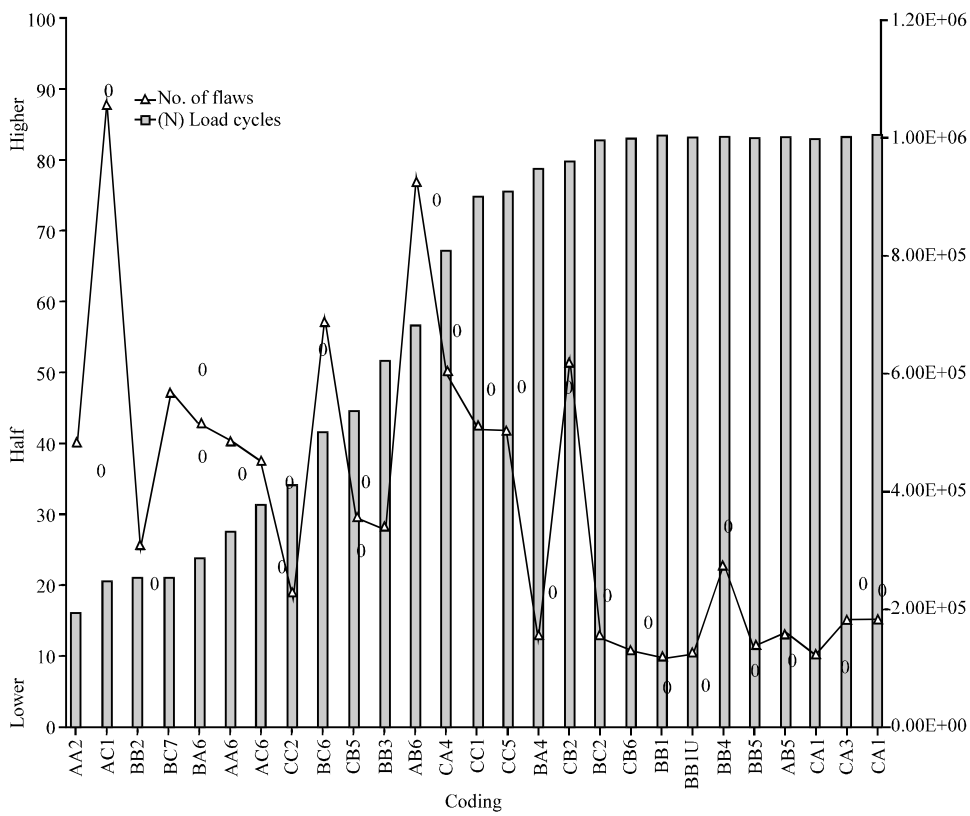
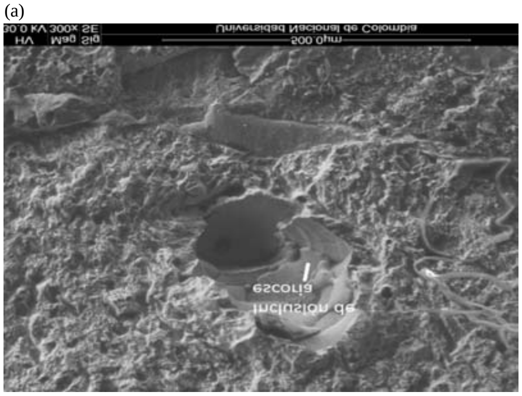


Fig. 5: Relationship between fatigue life and intensity of prestent flaws

(a)



(b)

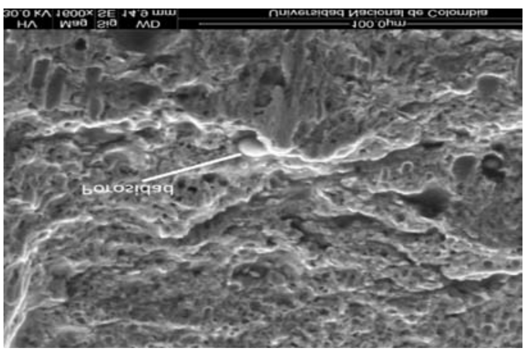


Fig. 6: Discontinuities type: a) Slag line and b) Porosity observed on the welded specimen BB7

Moreover, an analysis of one flaw using the scanning electronic microscopy on the cruciform fatigue sides of fatigue of the cruciform test piece in order to detect the different flaws in the fillet weld. Later to the flaw for fatigue. The previous thing allowed to confirm the existence of several of the flaws detected before by means of ultrasound in each of the fillet weld of test pieces.

Besides, it was possible to identify other types of discontinuities and singular formations in the sides of the crack, characteristic of this type of flaws. In many of the cases, it was possible to find the type of present flaw in the fillet weld, according to the typical indication obtained by the ultrasound device. Also, there was possible the detection of discontinuities in a low level.

In Fig. 6, a sample with a microstructure using the scanning electron microscope is made on the crack surface (test piece BB7) where an inclusion of slag and pores are identified. This type of flaws can appear due to the free gases by the welded metal cooling as a consequence of the reduction of solubility as the temperature decreases.

CONCLUSION

From the gathered outcomes by ultrasonic inspections it can be observed that, more intense cooling means can increase the probability to find more density and larger size of flaws in the fillet welded, such initial cracks and circular porosities in the welding. The latter act as drivers of stable propagation cracks and restrict the fatigue life of welded components. Both experimental factors chosen for the experimental design (size of the side and cooling means) resulted to be meaningful as greater size welded side, showed a higher probability in the emergence of flaws on the fillet weld. The latter can be related to bigger welded sides prompt larger residual stresses, facilitated by the need of a greater heat share to the joint and the greater tridimensional restriction to the thermal contraction that a greater fillet welded has.

One concludes the importance of using warm-up in the base material and guarantee the soft post-welded cooling curve in order to avoid the appearance of cracks in dangerous dimensions for the structural integrity of the welded joint. For the object of study in the present research, material base ASTM A36 HR, electrode E6013 and using procedure SMAW, post welded cracks of greater size and greater linear density were identified from the same features as when an intense cooling means as water was used. Nevertheless, it is interesting to report that the welded specimens in a great deal of times, ended up being wit tolerable flaws, according to the acceptance codes of flaws on welded joints.

The test of ultrasound turned out to be a non-destructive-but-effective technology for the identification of the initial flaws on welded joints. The ultrasonic indications allowed to build a map of the pore and crack flaws. There can be the clear difference between one and another type of flaw. It was not possible to know with certainty by means of ultrasonic inspection, the dimensions of the flaws. Nevertheless, it was an approximate estimation of the latter. Outstanding correspondence between the prediction of the ultrasonic test and the result to the analysis of flaw. The scanning electronic microscopy turned into the main tool for the characterization of the discontinuities into the microstructure of the metal.

ACKNOWLEDGEMENTS

The researchers wish to thank Direction de Investigation at Universidad de Ibague and Universidad Nacional de Colombia de la Sede Bogota for the support offered in conducting this research.

REFERENCES

Alam, M.S., 2005. Structural integrity and fatigue crack propagation life assessment of welded and weld-repaired structures. Ph.D Thesis, South Dakota School of Mines and Technology, Rapid City, South Dakota.

Anderson, T.L., 1994. Fracture Mechanics, Fundamentals and Applications. 2nd Edn., CRC Press, Boca Raton, Florida, USA., Pages: 687.

Araque de los Rios, O.J. and N. Arzola de la Pena, 2016. [Theoretical experimental study on the phenomenon of post-welding cooling in a cruciform welded joint (In Spanish)]. Ingeniare. Rev. Chil. Ing., 24: 228-238.

Attarha, M.J. and I. Sattari-Far, 2011. Study on welding temperature distribution in thin welded plates through experimental measurements and finite element simulation. J. Mater. Process. Technol., 211: 688-694.

Francis, J.D., 2001. Welding simulations of aluminum alloy joints by finite element analysis. Master Thesis, Virginia Tech, Blacksburg, Virginia.

Kou, S., 2003. Welding Metallurgy. 2nd Edn., Wiley-Inter-Science Publication, USA., pp: 37-59.

Maddox, S.J., 1994. Applying fitness-for purpose concepts to the fatigue assessment of welded joints. Proceedings of the 1994 International Conference on Fatigue Vol. 1, May 3-7 1994, Toronto, Ontario, Canada, pp: 72-81.

Mohsin, M.E.A., M. Elias, A. Arsad, A. Hassan and O.Y. Alothman, 2016. Ultrasonic irradiation: A novel approach for conductive polymer. J. Eng. Appl. Sci., 11: 2557-2560.

Wahab, M.A. and M.S. Alam, 2004. The significance of weld imperfections and surface peening on fatigue crack propagation life of butt-welded joints. J. Mater. Process. Technol., 153: 931-937.

Zhu, X.K. and Y.J. Chao, 2002. Effects of temperature-dependent material properties on welding simulation. Comput. Struct., 80: 967-976.