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Residual Stresses Measurement in Hollow Samples Using Contour Method

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ABSTRACT

Residual stresses are created usually undesirably during manufacturing processes, including casting, welding, metal forming, etc. Residual stresses alone or in combination with other factors can cause the destruction and fracture of components or significant decline in their service life. Therefore, it is crucial to measure the residual stresses. Contour method is a destructive testing method capable of measuring residual stresses of the cut surface along with being simple and low-cost. This method is able to create a two-dimensional map of residual stresses perpendicular to the sectioned surface. Measuring hollow samples is still a dilemma when using the contour method**.** In this study, hollow cylindrical samples with inner diameters of 20 and 40 mm were quenched at temperatures of 300ºC, 400ºC, and 850ºC. Both numerical analyses and experimental measurements were performed for the samples. The contour method was practiced for both hollow and filled samples. Overall review of the results was promising. However, the results obtained in the vicinity of the edges illustrated large deviations. Steel shafts were inserted to cylindrical holes to rectify the lack of constraint near the edges. The measurements on the filled samples were greatly improved.

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1. INTRODUCTION

Residual stresses are “locked-in” stresses which remain in the materials independent of external loads [1]. These are self-balancing tensile and compressive stresses in a part of materials and are in equilibrium in the whole body. Almost all manufacturing processes can create residual stresses and must be controlled in a way that averts development of such stresses [2]. Due to self-balancing feature of residual stresses, they might not be easily recognized and could be ignored during engineering design. However, they must be treated similar to stresses caused by external loading [3].

Several experimental methods are employed to measure residual stresses. Generally, these methods fall into two destructive and non-destructive categories [4, 5]. Contour method, which is a destructive technique, was founded and expounded by Prime in 2001 [6]. In this method contours originated from cross-cutting planes are measured. It is assumed that contour deviation of plane surface is due to release of residual stresses. Theoretical foundation of contour method is based on Buckner superposition principle [7]. In the early stages of this method, residual stresses were measured in welding of a steel plate and the subsequent results were compared to Neutron diffraction [8-10]. Also, the residual stresses caused by motion of an object resulting damage on a thick high-strength low-alloy steel plate, were determined using contour method and compared with numerical solutions [11, 12]. The measurement by contour method was then practiced for two thick butt-welded plates made of 2024-T351 and 7070-T7451 aluminum alloys and then was compared to Neutron diffraction [13]. The contour method has been applied for MIG weld [14], welded T-joint samples [15], quenched cylinders [16], shrink fitted components [17], friction stir welding [18], laser peened samples [19, 20] and many other applications. In addition, the possibility of measuring other components of residual stresses by 45-degree cuts has been examined [21]. Contour method has also been used to measure residual stresses in low thickness welded plates which are extensively used in piping and pressure vessels [22]. Residual stresses in hollow samples with low thicknesses have been

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determined by contour method and been compared with non-destructive neutron diffraction method [23]. Furthermore, the effect of plasticity on residual stresses measured by contour method has been regarded [16]. Some solutions were considered in order to minimize plasticity effect stemmed from the cutting process [24, 25]. Controlling the cutting process of the samples for edge-crack and double-embedded states illustrated that the contour method provided better results for the double-embedded state which was confirmed by Neutron and Synchrotron diffractions which was due to less plasticity during the cut for the case of double-embedded sample [25, 26]. Contour methods with asymmetrical cuts have also been practiced [26]. To improve the performance of the contour method many studies have been conducted. There are many researches focusing on the parameters and factors affecting this method and improving the accuracy have been carried out [27]. In most of contour method studies wire cut electro-discharge machining (wire cut EDM) has been chosen as a cutting method of the samples. The error caused by cutting has been studied with different cutting wires and different thicknesses [28]. The amount of error is largely due to the cutting process and can be reduced by applying the correct parameters such as wire feed speed, pulse intensity of spark, tension in wire, etc [29]. To date, the first step towards developing a standard and practical guideline on contour method has been taken [17]. In another research, Hossain et al.[29] examined a way of minimizing the distortion error in the contour method. The accuracy of the contour method has been studied by other researchers for additively manufactured samples [30] and weldments [31].

There is still lack of evidence on how the contour method would work near the edges especially in hollow samples. In the current research, residual stresses were induced within hollow cylinders and were measured using contour method. To improve the measurements, a metal shaft was inserted to the cylindrical hole and measurements were carried out for both hollow and filled samples. All numerical and experimental results are reported here.

2. THEORY

Contour method is based on releasing elastic stresses by material removal which can be used for large structures with both low and high thicknesses. Based on the theory of elasticity when a cut is put in the sample containing residual stresses the shape of the sample alters to maintain equilibrium [6]. The required amount of stress to return the shape to the pre-cut levels of deformation is equal to the residual stresses that are released during the cutting process [32].

Precise calculation of residual stresses in metal components by contour method relies on a quality cut, accurate measurement of deformations of the cut surface, and analysis of obtained data [17]. While cutting, plasticity may vary in the cutting tips which depend on the state of locked in residual stresses, gripping of the sample and the cutting method [33]. For instance, setting the wire under tension reduces the vibration and deviation; however it could lead to less quality cut surface [34]. When the wire reaches to the start and stop points of the cutting, a non-uniform flushing is developed according to limited diameter of flushing feed nozzles that can causes vibration of the wire. The effect seems to be more noticeable at the start and stop points of the cut. As soon as the cut penetrates a few mms in the sample or gets out of it, flushing stability is reduced [17, 35]. Flushing, with consideration of entry and exit of the wire and also at the start and stop points of the cut, depends on the properties of materials. In order to diminish the effects of the cutting wire, sacrificial layers have been used at both ends of the cut with the length of 10mm [36].

3. EXPERIMENTS

3. 1. Quenching

Quenching is rapid cooling of components in a specific temperature so as to obtain certain material properties. In this research, quenching was used to induce residual stresses in the samples. Six cylindrical samples were machined with 60mm height and 60mm diameter. Four of these samples were made with 20mm inner diameter and two samples had 40mm inner diameter. Two samples, which had inner diameter of 20mm, were quenched at 500ºC. Two other samples with 20mm inner diameter were quenched at 850ºC. The remaining samples which had the inner diameter of 40mm were quenched at 500ºC. Samples were initially heated to the desired temperature using an electrical furnace. Samples were immediately taken out of furnace and then were located inside a water spray cooling rig. The cooling set-up is shown in Figure 1.

Figure 1. Illustrating the water spray cooling rig

All samples were made of stainless steel 316L. Chemical composition (wt%) of this steel is shown in Table 1. Mechanical properties of this material has been taken from literature [37, 38] as the specimens were made from the block of material was used.

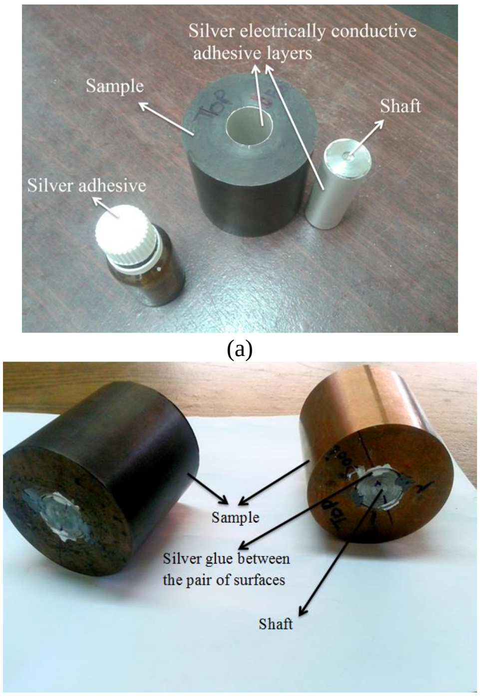
3. 2. Shaft Insertion Based on the information mentioned in the theoretical part when the cut penetrates a few mm in the component or when it gets out, flushing stability declines [17, 32]. To improve stability and steadiness of flushing, a shaft was employed as a sacrificial layer for the internal edges. The shaft was inserted to the cylindrical hole and was bonded using silver adhesive. The adhesive consists of a polymer adhesive and a filler material which is eclectically conductive. Creating electrical bridge between the shaft and the sample and increasing constraints (sacrificial layers) were the reasons why conductive silver adhesive was used. In this work, conductive silver adhesive of 40-45% purity with Nano-silver particles was used. To be able to compare the performance of the contour method between the cases of hollow and filled samples, shafts were inserted into some hollow samples. Two 20mm and one 40mm inner diameter samples were inserted using steel shafts using silver adhesive. Filled samples are shown in Figure 2.

3. 3. Cutting Process Cutting with the least possible contact is required to achieve a surface with low roughness and high accuracy. In contour method, it is essential that a single cut splits sample into two pieces and it is due to the fact that the subsequent cuts of the wire can wipe the information and deformations from the first cut which are required to calculate the residual stresses. However, there can be many problems with the wire cut EDM, such as discontinuities related to wire tearing, cut instability, temporary effects of the cut at the start and stop points, bulging and etc [27, 33]. A brass wire with diameter of 0.25mm was used to cut the samples. This wire size removed a film of material with 0.35mm thickness. A fixture was designed and manufactured to hold the samples while cutting as illustrated in Figure 3.

Comparing Figures 4 indicates that the quality of the edges improved when shafts were inserted to hollow samples. Figure 4(a) shows edges of the hollow sample and Figure 4(b) indicates those for the filled sample.

TABLE 1. Chemical compositions of steel 316L

C	Si	Mn	P	S	Cr	Mo	Ni	Al	Co	Cu	Nb	V	W	N
0.02	0.51	1.5	0.03	0.023	16.9	2.1	10.1	0.011	0.12	0.35	0.01	0.06	0.04	0.06



(a)

(b)

Figure 2. (a) silver adhesive layer on the sample, (b) Filled samples with silver adhesive

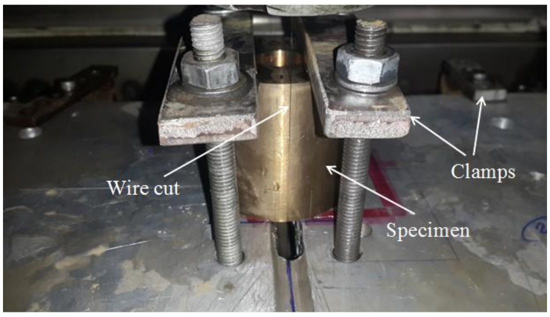
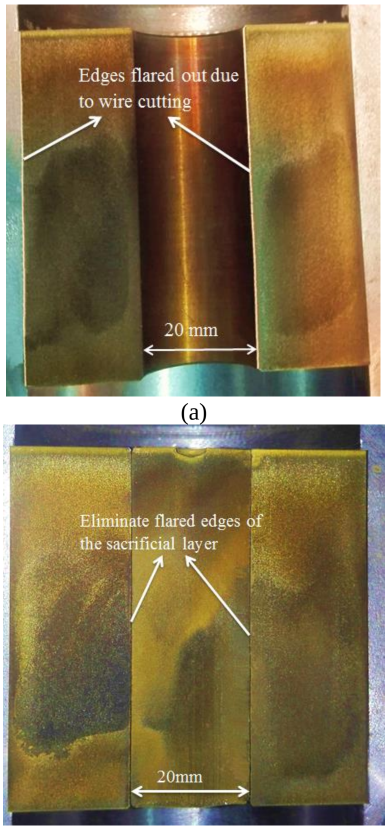


Figure 3. Fixture and the sample while cutting

3. 4. Measuring Deformations Distortions were measured in both cut planes with a touch coordinate measuring machine (CMM). The machine benefited from a 1mm diameter probe and measurement accuracy of 0.1 micron. The sensor of the CMM had a continuous motion in contact with sample surface dragging from one edge to the other. The way the probe touches the surface is shown in Figure 5. The faster probe moves, the less accuracy will be obtained; consequently, level of errors increases.

3. 5. Averaging The measured surface displacements normally include noises. Existence of dirt, scratch, and any defect on the surface causes increase in error of displacement of points on the surface [6]. Furthermore, there are some other errors which must be diminished after reducing surface errors and before applying the obtained data to the finite element model as boundary conditions. Thus, by averaging the displacements of both sides, all asymmetric errors of cutting were corrected. The average of the enclosed displacements exclusively shows the effects of normal stresses in the sectioned plane. A sample of smoothed data for hollow cylinder quenched at temperature of 850ºC is illustrated in Figure 6.



(a)

(b)

Figure 4. Comparing the cut surfaces, (a) Hollow sample, (b) Filled sample

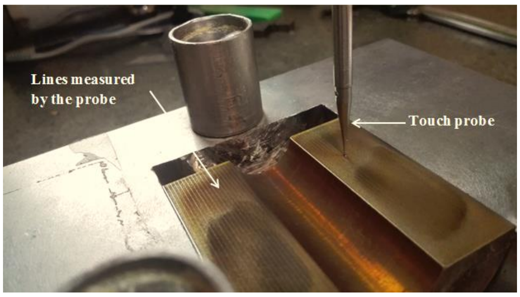
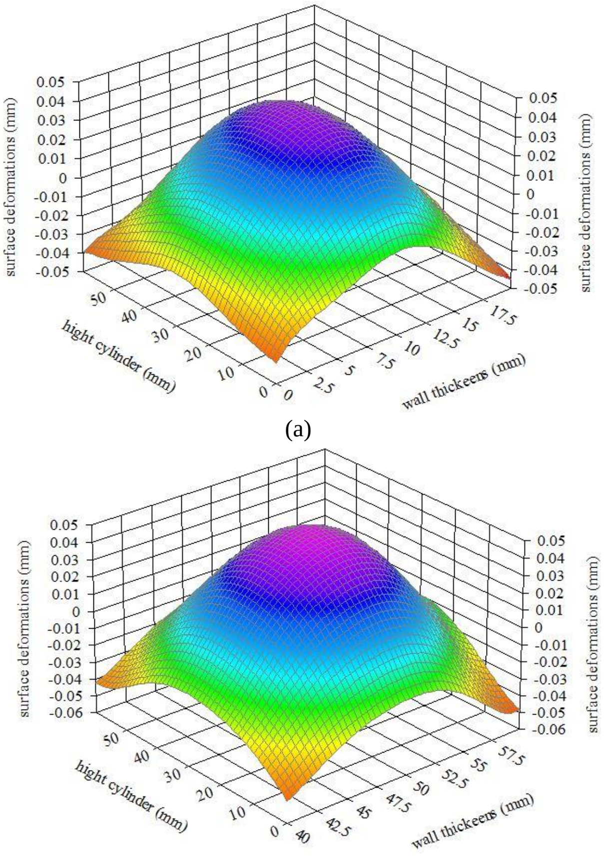


Figure 5. Indicating probe movement and the measured lines

The obtained results from averaged surfaces by consideration of peak-to-valley distance in displacement contours for thick samples were 75 and 110 microns for samples quenched at 500ºC and 850ºC, respectively. This amount for the thin-walled sample quenched at 500ºC was around 38 microns.

3. 6. Applying Displacements as Boundary Conditions to a Finite Element Model

Not only is contour method not merely an experimental approach but also it is required to apply average of displacements as boundary conditions to a finite element model. In the experiments, due to impossibility and complexity of changing the deformed surface to a flat surface, DISP subroutine from ABAQUS was used to apply the boundary conditions. Figure 7 shows displacement applied to one of half-cylindrical samples with magnification.



(a)

(b)

Figure 6. smoothed data for hollow cylinder quenched at the temperature of 850ºC

4. NUMERICAL ANALYSES

Two independent thermal and mechanical analyses were carried out to perform uncoupled simulation of the quenching process. Firstly, a thermal analysis was done in which temperature was the only degree of freedom for nodes. Temperature changes during the process were recorded and subsequently in a static analysis the temperature history was applied as boundary conditions. One point on the bottom surface of the cylinder was fixed along z and y directions (directions are shown in Figure 7). It is crucial to apply forced convection heat transfer; other types of heat transfer such as radiation and conduction were neglected.

The cylindrical samples were 60*60mm with inner diameters of 20 and 40mm. Simulations for the samples mentioned above were performed according to the experiments. For thermal simulation coefficient of conductivity, specific heat, density, and mechanical properties of material were required. Thermal and mechanical properties of steel 316L are illustrated in Table 3.

Due to thermal analysis, a thermal step with transient respond was defined. The time for taking this step pending the temperature of the surface reaches 23ºC was 360 seconds. The coefficients of convection for all dimensions subjected to heat transfer for curved and flat surfaces was 7000 and 3500 $\left({}^{\mathrm{W}}/_{\mathrm{m^2K}}\right)$, respectively according to literature [16]. Number of elements for samples with 20 and 40mm inner diameter was 148800 and 122550, respectively. The mesh was refined near the edges and cutting lines to a element size of 0.33mm. The element used for thermal analysis was DC3D8 which is an eight-node cube with temperature being the only degree of freedom.

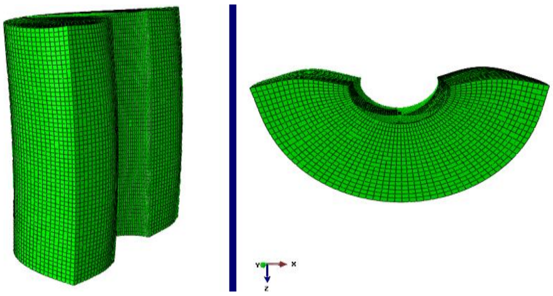


Figure 7. Applying the measured displacement to the half cylinder as boundary conditions with magnifications

4. 1. Contour Method

In contour method simulation as experimental state, sample was divided into two parts and solid deformations, which stem from stress release, were measured based on relations (1) and (2). Equations (1) and (2) provide the deformation for the right and left cut surfaces, respectively.

$$U_{n\,(Right\,surface)} = (U_n)_{after\,cut} - (U_n)_{before\,cut} \qquad (1)$$

$$U_{n(Left\,surface)} = (U_n)_{before\,cut} - (U_n)_{after\,cut} \qquad (2)$$

Eventually, by smoothing data and deformations in reverse direction as boundary conditions of finite element half-model, residual stresses were calculated. In this research all charts and stress contours contain normal component to the cut surface. Tie constraint can combine two surfaces from two different areas with different meshing so that there is no relative motion between them. It is noteworthy to use tie constraint to stick shaft inside the cylinder in the cylinder-shaft model.

5. RESULTS AND DISCUSSION

Residual stresses obtained from the experimental practice of contour method were compared with the results derived from the numerical both simulations of quenching and contour method. In fact, three results from numerical simulations were compared with two experimental results. In order to enhance the comparison, the analyzed paths are shown in Figure 8.

TABLE 3. Thermal and mechanical properties of steel 316L [**Error! Bookmark not defined.**]

	Temperature (°C)									
Properties	**20**	**100**	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**
Young's modulus (GPa)	196	191	186	180	173	165	155	144	131	117
Poisson's ratio	0.294	0.294	0.294	0.294	0.294	0.294	0.294	0.294	0.294	0.294
Thermal conductivity (W/m°C)	14.12	15.26	16.69	18.11	19.54	20.96	22.38	23.81	25.23	26.66
Specific heat (J/Kg°C)	492	502	514	526	538	550	562	575	587	599

	Temperature (°C)						
Yield stress (MPa)	20	300	400	500	600	700	850
	245.49	153.31	145.29	135.37	126.25	110.22	82

	Temperature (°C)					
Thermal expansively (1/°C)	0	30	200	315	650	800
	$1.2e^{-6}$	$5e^{-6}$	$1.25e^{-5}$	$1.33e^{-5}$	$1.47e^{-5}$	$1.5e^{-5}$

(b) (a)

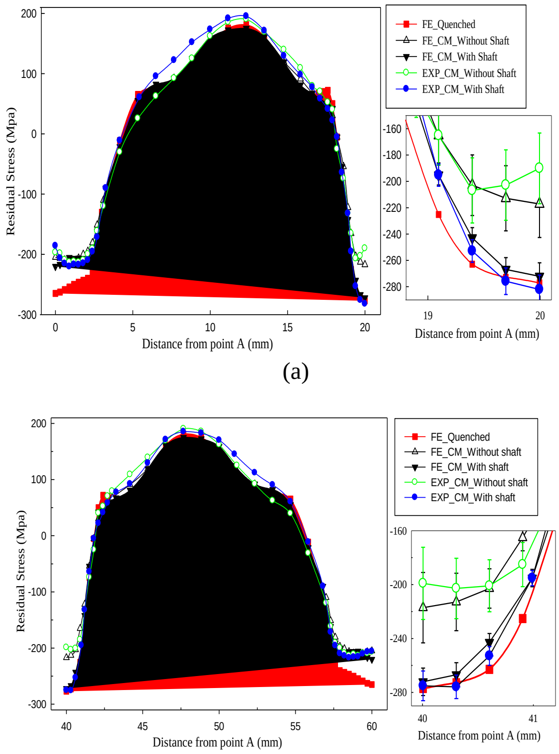
Figure 8. Comparing paths on samples with, (a) 20mm inner diameter, (b) 40mm inner diameter

In all subsequent figure legends “FE_Quenched” refers to the residual stresses obtained from finite element simulation of the quenching process. “FE_CM” refers to the results of contour method simulation can be with or without inserted shaft. Finally, “EXP_CM” refers to the experimental measurements using the contour method which were performed with and without shaft.

Fundamental assumption of the contour method rests on the release of mechanical strains in the elastic region. It is essential that results obtained from contour method in numerical simulations and experimental measurements be in good agreement with original residual stresses from quenching; however, as results shown in Figures 9-11, it was not the case near the edges of the sample. Differences between results are because of cutting error which is more noticeable near the edges. Differences between errors exist due to violation of contour method fundamental assumption. By constraining the sample during the cut, plasticity error can be considerably regulated. But in the edges, due to lack of constraints in comparison to internal parts, when the residual stress releases, material in this areas show less resistance and consequently more areas experience plastic region. Cutting causes flared edges because there are less constraints near the edges. The magnitude of residual stresses does not have any effect on the flared edges and the error is barely due to lack of constraints in the area; the reasons of errors and ways to control them have been investigated in literature [16].

As it can be seen in Figures 9-11, the use of sacrificial layers produced suitable results in the internal edges. It is clear that the numerical and experimental results have a great correlation. Thus, results obtained from the experiments validated contour method numerical simulation. It is worth to note that for the sample quenched at higher temperature the mount of error near the edges was greater when no internal shaft was used. This was due to the more plasticity occurring when the cut was put in. The most stress deviations appeared near the edges which was due to the start and stop of the cut. However, part of the measurement errors and surface defects were diminished in distortion conformity on polynomials. Errors mostly occurred at a distance of 2-3 mm from the edges. As it can be seen in Figure 9, residual stresses in thinner sample were lower than the thick one, so results derived from contour method had a better agreement although there are errors at the edges.

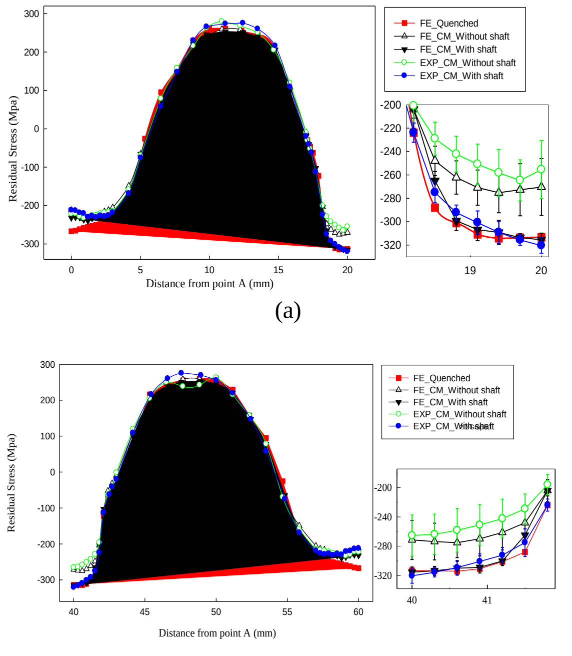
In order to have a better understanding of how inserting a shaft can reduce the errors in hollow samples, the amount of errors was calculated using Equation (3).



(a)

(b)

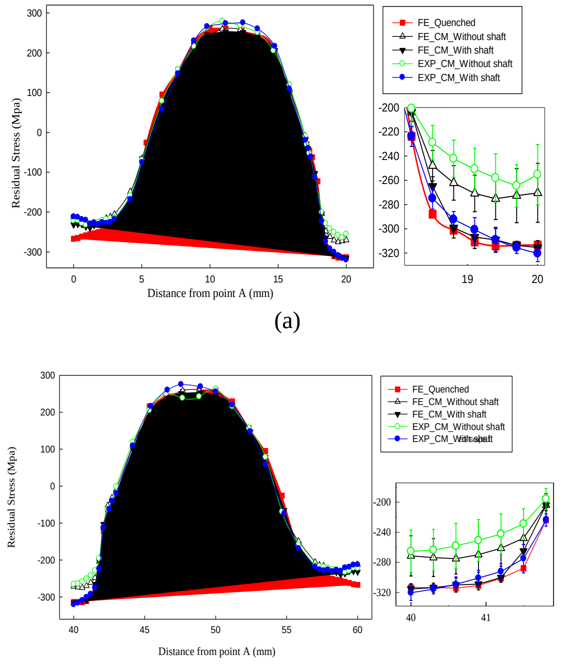
Figure 9. Comparison of the between residual stresses obtained from numerical analyses and experiments for sample quenched at 500ºC, 20mm inner diameter, (a) Path AB, (b) Path CD



(a)

(b)

Figure 10. Comparison of the between residual stresses obtained from numerical analyses and experiments for sample quenched at 850ºC, 20mm inner diameter, (a) Path AB, (b) Path CD



(a)

(b)

Figure 11. Comparison of the between residual stresses obtained from numerical analyses and experiments for sample quenched at 500ºC, 40mm inner diameter, (a) Path AB, (b) Path CD

The residual stresses obtained from the simulations and the experiments were compared to the quenching residual stresses from the finite element model. In the equation, $\sigma_{Methods}$, refers to the residual stresses obtained from the experiment or simulation of the contour method.

$$Error\ (\%) = \frac{(\sigma_{Quenched} - \sigma_{Methods})}{\sigma_{Quenched}} \times 100 \qquad (3)$$

It is noticeable that inserting the shaft reduced the amount of mean error from more than 20% to less than 8% for the sample quenched at 850ºC as shown in Figure 12. Shaft insertion also decreased the errors for the sample quenched at 500ºC to 6% for both hollow samples. The amount of errors were averaged for a surface along the edge and 2mm further from it which is basically the area affected by the flared edge.

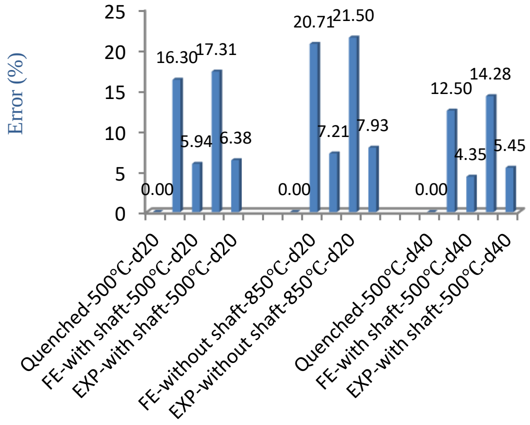


Figure 12. Mean value of errors

6. CONCLUSIONS

Best results for surfaces were obtained from polynomial of 4th and 5th order of Chebyshev and Fourier 2*3 series.

Using electrical conductive adhesives did not add additional residual stresses.

By use of sacrificial layers lack of constraints and non-uniformity of cutting at the edges can be compensated and errors of plasticity and flared edges will be reduced.

Contour method is an easy and efficient method for both thin and thick hollow samples due to its suitable accuracy, especially at edges of samples with a shaft inside.

7. ACKNOWLEDGEMENT

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7. REFERENCES

1. Totten, G.E., "Handbook of residual stress and deformation of steel, ASM international, (2002).
2. Prime, M.B., "Residual stress measurement by successive extension of a slot: The crack compliance method", ***Applied Mechanics Reviews***, Vol. 52 (1999) 75-96.
3. Withers, P., "Residual stress and its role in failure", ***Reports on Progress in Physics***, Vol. 70, No. 12, (2007), 2211-2264.
4. Withers, P.J. and Bhadeshia, H., "Residual stress. Part 1– measurement techniques", ***Materials Science and Technology***, Vol. 17, No. 4, (2001), 355-365.
5. Johnson, G., "Residual stress measurements using the contour method, The University of Manchester (United Kingdom), (2008).
6. Prime, M.B., "Cross-sectional mapping of residual stresses by measuring the surface contour after a cut", ***Journal of Engineering Materials and Technology***, Vol. 123, No. 2, (2001), 162-168.
7. Bueckner, H., "The propagation of cracks and the energy of elastic deformation", ***Transaction of the ASME, Series E***, Vol. 80, No. 6, (1958), 1225-1230.
8. Zhang, Y., Pratihar, S., Fitzpatrick, M.E. and Edwards, L., "Residual stress mapping in welds using the contour method", in Materials science forum, Trans Tech Publ. Vol. 490, (2005), 294-299.
9. Prime, M., *Weld application of a new method for cross-sectional residual stress mapping*. 2001, Los Alamos National Lab., NM (US).
10. Zhang, Y., Ganguly, S., Edwards, L. and Fitzpatrick, M., "Cross-sectional mapping of residual stresses in a vppa weld using the contour method", ***Acta Materialia***, Vol. 52, No. 17, (2004), 5225-5232.
11. Prime, M.B. and Martineau, R.L., "Mapping residual stresses after foreign object damage using the contour method", in Materials science forum, Trans Tech Publ. Vol. 404, (2002), 521-526.
12. Prime, M.B., *Residual stresses measured in quenched hsla-100 steel plate*. 2005, Los Alamos National Laboratory.
13. Prime, M.B., Gnäupel-Herold, T., Baumann, J.A., Lederich, R.J., Bowden, D.M. and Sebring, R.J., "Residual stress measurements in a thick, dissimilar aluminum alloy friction stir weld", ***Acta Materialia***, Vol. 54, No. 15, (2006), 4013-4021.
14. Richter-Trummer, V., Tavares, S.M., Moreira, P.M., de Figueiredo, M.A. and de Castro, P.M., "Residual stress measurement using the contour and the sectioning methods in a mig weld: Effects on the stress intensity factor", ***Ciência & Tecnologia dos Materiais***, Vol. 20, No. 1-2, (2008), 114-119.
15. Murugan, N. and Narayanan, R., "Finite element simulation of residual stresses and their measurement by contour method", ***Materials & Design***, Vol. 30, No. 6, (2009), 2067-2071.
16. Mahmoudi, A., Hosseinzadeh, A.R. and Jooya, M., "Plasticity effect on residual stresses measurement using contour method", ***International Journal of Engineering, Transactions A: Basics***, Vol. 26(10) (2013) 1203-1212.
17. Hosseinzadeh, F., Kowal, J. and Bouchard, P.J., "Towards good practice guidelines for the contour method of residual stress measurement", ***The Journal of Engineering***, Vol. 2014, No. 8, (2014), 453-468.
18. Liu, C. and Yi, X., "Residual stress measurement on aa6061-t6 aluminum alloy friction stir butt welds using contour method", ***Materials & Design***, Vol. 46, (2013), 366-371.
19. Toparli, M. and Fitzpatrick, M.E., "Development and application of the contour method to determine the residual stresses in thin laser-peened aluminium alloy plates", ***Experimental Mechanics***, Vol. 56, No. 2, (2016), 323-330.
20. Toparli, M., Fitzpatrick, M.E. and Gungor, S., "Improvement of the contour method for measurement of near-surface residual stresses from laser peening", ***Experimental Mechanics***, Vol. 53, No. 9, (2013), 1705-1718.
21. DeWald, A. and Hill, M., "Multi-axial contour method for mapping residual stresses in continuously processed bodies", ***Experimental Mechanics***, Vol. 46, No. 4, (2006), 473.
22. Turski, M. and Edwards, L., "Residual stress measurement of a 316l stainless steel bead-on-plate specimen utilising the contour method", ***International Journal of Pressure Vessels and Piping***, Vol. 86, No. 1, (2009), 126-131.
23. Prime, M.B., Contour method advanced applications: Hoop stresses in cylinders and discontinuities, in Engineering applications of residual stress, volume 8. 2011, Springer.13-28.
24. Hosseinzadeh, F., Traore, Y., Bouchard, P. and Muránsky, O., "Mitigating cutting-induced plasticity in the contour method, part 1: Experimental", ***International Journal of Solids and Structures***, Vol. 94, (2016), 247-253.
25. Muransky, O., Hamelin, C.J., Hosseinzadeh, F. and Prime, M.B., "Mitigating cutting-induced plasticity in the contour method. Part 2: Numerical analysis", ***International Journal of Solids and Structures***, Vol. 94, (2016), 254-262.
26. Mahmoudi, A. and Saei, A., "Influence of asymmetrical cuts in measuring residual stresses using contour method", ***International Journal of Pressure Vessels and Piping***, Vol. 134, (2015), 1-10.
27. Prime, M.B. and Kastengren, A.L., The contour method cutting assumption: Error minimization and correction, in Experimental and applied mechanics, volume 6. 2011, Springer.233-250.
28. Ahmad, B. and Fitzpatrick, M.E., "Minimization and mitigation of wire edm cutting errors in the application of the contour method of residual stress measurement", ***Metallurgical and Materials Transactions A***, Vol. 47, No. 1, (2016), 301-313.
29. Werke, M., Hossain, M., Semere, D. and Wretland, A., "Machining distortion analysis of aerospace components using the contour method", in FT2019. Proceedings of the 10th Aerospace Technology Congress, October 8-9, 2019, Stockholm, Sweden, Linköping University Electronic Press. (2019), 216-222.
30. Ahmad, B., van der Veen, S.O., Fitzpatrick, M.E. and Guo, H., "Residual stress evaluation in selective-laser-melting additively manufactured titanium (ti-6al-4v) and inconel 718 using the contour method and numerical simulation", ***Additive Manufacturing***, Vol. 22, (2018), 571-582.
31. Liu, C., Wang, C., Cheng, X., Yan, Y., Yang, J. and Guo, Y., "Experimental investigation on the residual stresses in a thick joint with a partial repair weld using multiple-cut contour method", ***Materials***, Vol. 11, No. 4, (2018), 633.
32. Schajer, G.S., "Practical residual stress measurement methods, John Wiley & Sons, (2013).
33. Traore, Y., Bouchard, P.J., Francis, J. and Hosseinzadeh, F., "A novel cutting strategy for reducing plasticity induced errors in residual stress measurements made with the contour method", in ASME 2011 pressure vessels and piping conference, American Society of Mechanical Engineers Digital Collection. (2011), 1201-1212.
34. Kunieda, M., Lauwers, B., Rajurkar, K.P. and Schumacher, B., "Advancing edm through fundamental insight into the process", ***CIRP Annals***, Vol. 54, No. 2, (2005), 64-87.
35. Bouchard, P.J., Ledgard, P., Hiller, S. and Hosseinzadh Torknezhad, F., "Making the cut for the contour method", (2012). http://oro.open.ac.uk/id/eprint/34114

36. Hosseinzadeh, F., Ledgard, P. and Bouchard, P., "Controlling the cut in contour residual stress measurements of electron beam welded ti-6al-4v alloy plates", ***Experimental Mechanics***, Vol. 53, No. 5, (2013), 829-839.
37. Mahmoudi, A. and Hasani, A., "A modification to the cross slitting method for measuring two components of residual stresses", ***The Journal of Strain Analysis for Engineering Design***, Vol. 52, No. 2, (2017), 93-101.
38. Mahmoudi, A., Hosseinzadeh, A. and Jooya, M., "Experimental calibration of the convection heat transfer coefficient in quenching process for a reliable prediction of residual stresses", in The International Conference on Experimental Solid Mechanics and Dynamics (X-Mech), Technology, U. o. S. a., Editor., (2012).

Persian Abstract

چکیده

تنش‌های پسماند به طور ناخواسته در حین فرآیندهای تولید، مانند ریخته‌گری، جوشکاری، شکل‌دهی و... ایجاد می‌شوند. با توجه به شکست قطعات بدون وجود بار خارجی، باعث شده که به‌راحتی اثر تنش‌های پسماند نادیده گرفته شود. تنش‌های پسماند، گاهی اوقات به‌تنهایی و گاهی در ترکیب با عوامل دیگر موجب تخریب قطعات و یا باعث کاهش شدید عمر آن‌ها می‌شود. بدین منظور اندازه‌گیری تنش‌های پسماند ضروری است. یکی از روش‌های مخرب اندازه‌گیری تنش پسماند روش کانتور است. این روش، قابلیت اندازه‌گیری تنش‌های پسماند سطح برش خورده را با روشی نسبتاً ساده و ارزان داراست. روش کانتور توانایی توصیف یک نقشه کامل دوبعدی از تنش پسماند عمود بر صفحه برش را دارد. در زمینه‌ی روش کانتور تا به حال فعالیت‌های متنوع و زیادی انجام شده، ازجمله می‌توان به بررسی خطاهای به وجود آمده در این روش اشاره کرد. در سال‌های اخیر کانون توجه محققین به بررسی منشا خطاهای به وجود آمده در حین برش وایرکات و همچنین پارامترهای کنترل این خطاها معطوف شده است. مطالعه‌ی پیش رو برای نمونه‌های توخالی استوانه‌ای شکل با دو قطر داخلی ۲۰ و ٤٠ میلی‌متری در سه دمای کوئنچ ۳۰۰°C، ۵۰۰°C و ۸۵۰°C انجام شد. در آزمایش‌های تجربی چهار نمونه با قطر داخلی ۲۰ میلی‌متر در دو دمای ۵۰۰°C، ۸۵۰°C و همچنین دو نمونه با قطر داخلی ٤٠ میلی‌متر در دمای ۵۰۰°C کوئنچ شدند و تنش‌های پسماند آن‌ها توسط روش کانتور اندازه‌گیری گردید. نتایج اندازه‌گیری در همه نقاط بجز لبه‌های نمونه‌ها قابل قبول بود. خطا در لبه‌ها ناشی از پارامترهای دستگاه برش و همچنین کمبود قیود ماده در لبه‌ها است. در این پژوهش برای جبران قیود مادی لبه‌های داخلی نمونه، نیمی از نمونه‌های تو خالی با فولاد زنگ نزن پر شدند که نتایج بسیار خوبی در لبه‌های نمونه حاصل شد.