VOL. 11, NO. 9, MAY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

REVIEW ON WELDING RESIDUAL STRESS

Nurul Syahida Mohd Nasir, Mohammad Khairul Azhar Abdul Razab, Sarizam Mamat, Muhammad Iqbal Ahmad
Advanced Materials Research Cluster, Faculty of Earth Science, University Malaysia Kelantan, Jeli, Kelantan, Malaysia
E-Mail: nurulsyahida004@yahoo.com.my

ABSTRACT

Residual stress classified as secondary stress that exist after all loads been removed. Residual stress can be favorable or detrimental to some components, depend on its type. Usually, tensile residual stress can cause harm to components while compressive residual stress can improve the component quality. Residual stress, either tensile or compressive present in almost all manufactured components. Both residual stresses, either tensile or compressive can be found in welding components. Many researchers agreed that tensile residual stress can be found in the weld metal area, but the compressive residual stress distribution is complex. The distribution welding residual stress varies in different locations depends on welding parameters, types, sequence, component type, component materials and component sizes. This review paper provides the information of welding residual stress and their distribution. This paper can help and giving idea to researchers on planning their welding work with a minimum value of residual stress.

Keywords: residual stress, residual stress distribution, welding.

1. INTRODUCTION

Stress is defined as the average force per unit area of some particle of a body. In material, stress can be identified as the internal distribution of forces within a body that balance and react to the loads applied to it [1]. Stress can be classified as primary (load-controlled) and secondary (displacement controlled) stress. Primary stress is the stress that applied in the component by system while the secondary stress in the component was applied by thermal [2]. Primary stress is the stress that caused by external applied loads such as hoop stress in a pressurized vessel, pipe or reactor. Secondary stress caused by the constraint of adjacent regions or imposed displacement fields such as the stress that caused by thermal expansion, welding thermal gradients or imposed plastic strains. Researchers agreed that residual stress can be classified as secondary stress. The stress exist within components due to imposed displacement without any external applied loads [3, 4].

2. RESIDUAL STRESS

Definition

Residual stress is the stress that exist within a component when there are no external load are applied to it [2]. In [5] identify residual stress as the stress that remain within a material or body after manufacture and material processing in the absence of external forces or thermal gradients. Residual stress also may arise from geometrical misfits in the natural shape between different regions, parts or phases [3, 6]. So, any remaining or residue stress that exists in a process component either in thermal or mechanical method without any applied external loads can be identified as residual stress.

Origin

Residual stress can present in unprocessed and processed materials. The residual stress within the process material was introduced during manufacturing and in-service loading. Residual stress originates from many sources. According to [7], residual stress can be originated by metallurgical (e.g.: heat treatment, welding, casting and metal forming operation) and mechanical (e.g.: shoot peening, machining and grinding) process. In [5] classified the origin of residual stress into three parts which were residual stress that come from the differential plastic flow, residual stress that come from different cooling rates and residual stress that exist from phase transformations with volume changes. Meanwhile, in [4] mention that the residual stress origin can be from mechanical, thermal, plastic or from transformation. But, they conclude that all residual stress come from the misfit.

Scale

Residual stress can be grouped into two scales namely macro and micro residual stress, which characterized by the scale at which they exist within a material. Stresses that occur over long distances within a material are referred as macro residual stresses, while stresses that exist either between grains or inside a grain are called micro residual stresses. Micro residual stress often results from the presence of different phases in a material [8] form after the components applied with thermal stress, loading stress, transformation stress and intergranular stress [9]. There were three types of residual stress scale existed namely type I: macro residual stress or macrostress, type II: micro residual stress or intergranular stress and type III: micro residual stress or atomic-scale stress [2-5, 8-10].

Type I is the stress that exists in the body of a component on a scale larger than the grain size of the material. In [9] mention that type I stress origin from misfit that exist from nitriding, peening, cold hole expansion and welding. This stress can be found in plastically deform materials, example in shot-peened surface and welded materials. Type II is the stress that varies with the scale of an individual grain.

It is the transformation stress of grains in different orientations, while type III is the stress that exist within several atomic distance of single grain [11] due to coherence at interfaces, crystalline defects and dislocation stress fields [3, 9].

Types

When a force is applied to an elastic material, the material will deform depend on the type of force applied to it. Normally, there are three types of force which are compressive force, tensile force and shear force that produce three basic types of stress which are compressive stress, tensile stress and shear stress. So, if a compressive force applied to a material, the stress tends to compress or shorten the material. This stress is called compressive stress. But when a tensile force applied to a material, the stress tends to stretch or lengthen the material which cause tensile stress. Shearing stress will occur if the stress tends to shear the material by the shear force.

There are two common stresses that present in residual stress, which are tensile stress and compressive stress. Tensile residual stress or compressive residual stress depends on the location and type of non-uniform volumetric change taking place due to thermal (welding and heat treatment) and process (contour rolling, machining and shot peening). Tensile residual stress at surface normally harmful and can cause brittle fracture, but compressive residual stress at the surface normally will increase fatigue strength.

Operation such as welding, machining, grinding and rod or wire drawing can cause harm and can give tensile residual stress to components [5]. While surface treatments such as shoot peening give the compressive residual stress, which can enhance performance for components [12-14]. Most of the surface treatments can induce compressive residual stress, but if it had been done in the right way [7]. Mostly, metallurgical process such as heat treatment [15] and welding introduce compressive residual stress to components. But, welding introduce both tensile and compressive residual stress to the component where it gives different stress at different location especially in welding components [5, 6, 16, 17]. While surface finishing like grinding cause tensile residual stress to components [18]. Grinding also should be avoided because it will introduce additional surface residual stress to components [19].

Welding residual stress

Nowadays, welding had been applied in many field such as construction, piping, shipbuilding, aircraft and aerospace, automotive, railroad, farm equipment, home appliances, mining equipment, computer components and construction equipment [20, 21]. Welding is a joining process of two or more metal parts to form a single product [22] and it is used to produces a secure and strong joint that is stronger than other methods of bonding metals. Welding is a process that involves localized heat generation from moving heat source. The welded structures heated rapidly up to the melting temperature, and followed by rapid cooling that cause microstructural and property alteration which leads residual stress [23]. Residual stress that exists in welded components is the results from the non-uniform expansion and compressive of the weld and the base material due to the non-uniform heat distribution during the welding process. Based on [24], residual stress that exists in weldment is due to the localized heating and rapid cooling.

Mostly, residual stress that found in welding components are harmful tensile stress which gives negative effect to the welding components. But, some researchers find that compressive residual stress that can bring benefit to the welding components. Tensile residual stress may lead to crack initiation to the welding component, while compressive residual stress can improve the component quality. The principal source of welding residual stress are shrinkage, quenching and phase transformation. Tensile residual stress occur due to the shrinkage while compressive residual stress affected by the quenching and phase transformation process [25]. Both tensile and compressive residual stress exist in welding component, but its distribution depends on location. Welding component can be improved by applying specific treatment to certain location based on the residual stress distribution data. So it is important to identify the welding residual stress distribution to improve its quality and reduce the negative effect to the welding component.

Distribution

There are many factors that affect the residual stress distribution in weldment components. According to [26], this is the factor that affects the distribution of residual stress in weldment components:

i. The existence of residual stress before welding (manufacture and fabrication)
ii. Material properties (weld and parent metal)
iii. The geometry of the joined components
iv. Restrain applied
v. Welding procedure
vi. Operation after welding

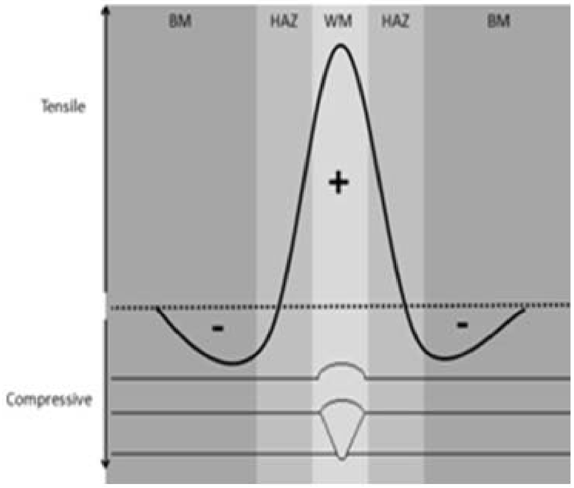


Figure-1. Welding residual stress distribution.

Figure-1 shows the distribution of welding residual stress. It shows that tensile residual stress exists in the weld metal zone and Heat Affected Zone (HAZ) while compressive residual stress mostly exist in base metal. It means that both tensile and compressive residual can exist in weldment components. However, Table-1 shows not all tensile residual stress occur at weld metal and not all compressive residual stress occur at base metal and HAZ. Certain research found both stress at the same zone and this is due to some factor that affect the residual stress distribution. Here are some other factors that also affect the residual stress distribution.

Material specification (base and filler material)

In [33] prove that steel type influence residual stress. It founds that for low carbon steel (S15C) has an insignificant effect on the welding (tungsten inert gas (TIG) arc welding) residual stress, but there is a significant effect on the welding residual stress of medium carbon steel (S45C). In the study, compressive stress exists in the fusion zone. While, high tensile stress existed in the weld zone.

There are difference in welding stress distribution between steel type (plate and pipe). Usually, a steel plate (Figure-1) welding produces tensile residual stress located in the weld area [5, 16, 17, 27, 31, 32] while compressive residual stress can be found mostly at HAZ zone [16, 27, 31, 32]. But, the steel plate stress distribution different from the pipe stress distribution. In [34] found the existence of residual stress at HAZ of multipass narrow gap welding of thick-walled stainless steel pipe, but the distribution are different between inner and outer surface. Near the inner surface, they found the compressive residual stress while they found tensile residual stress near the outer surface of the pipe.

Table-1. Welding residual stress distribution.

Author	Compressive Residual Stress	Tensile Residual Stress
Rossini et al. [5]	➢ Weld toe zones	➢ Weldment
Ju et al. [16]	➢ HAZ (CGHAZ) ➢ Base metal	➢ Centerline of weld
Kannengiesser and Kromm [27]	➢ Boundary of weld to HAZ	➢ Weld center
Wu [28]	➢ -	➢ Fusion zone
Monin et al. [29]	➢ -	➢ Near weld zone
Paddea et al. [17]	➢ Weld metal	➢ Near the HAZ outer boundary ➢ Towards the weld root region
Vemanaboina et al. [30]	➢ Base metal (transverse) ➢ Weld bead	➢ Higher at fusion line compared to HAZ
Bussu and Irving [31]	➢ HAZ ➢ (complex distribution)	➢ Weld ➢ HAZ (complex distribution)
Pouget and Reynolds [32]	➢ Vicinity of weld ➢ HAZ	➢ Weld nugget

In [35] also agreed that stress distribution of pipe is different between the inner and outer surface. But from the study, they mention that steel condition also influence the stress distribution. The study compares the residual stress between thin and thick stainless steel pipe welds and they found that there is tensile stress occurring nearer to the inside surface of the pipe thin-wall welded pipes. They assume that the compressive stress occurs nearer to the outside surface of the pipe. While, there is a difference residual stress distribution in thick-wall welded pipes. They state that tensile stress occurs near to the pipe outside surface and assuming compressive stress occurs nearer to the inside surface of the pipe. They also mention that pipe diameter in the thin walled influence the residual stress measurement.

The combination between steel and electrode also play role in welding residual stress distribution. Table-2 shows the welding residual stress distribution by three different parameters. The residual stress distribution result in the same material (austenitic) for both steel and electrode obtains same distribution as Figure-1. However, when using different material for steel and electrode the residual stress distribution will be differ.

VOL. 11, NO. 9, MAY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

Welding process

In [36] compare the residual stress between welding process TIG (tungsten inert gas) and A-TIG (activated flux tungsten inert gas) of 316LN stainless steel. For both welding, the tensile residual stress located close at the weld metal while the compressive residual stress away from weld metal. Between TIG and A-TIG welding process, A-TIG gave the lower tensile residual stress. They advise to choose A-TIG welding process to minimize residual stress.

Welding parameter (Heat Input)

In [37] had conducted a research on heat input thermal and residual stresses in a welded structure. From the research, it founds that heat input does influence the temperature distribution but there is no linear effect on residual stress. But, it mentions that better to use smaller heat input to obtain smaller magnitude of residual stress. According to [38], heat input does affect the value and distribution of residual stress. In [6] state that welding parameter influence the residual stress distribution. Compressive residual stress exists near to weld center line when low heat input applied to the components. When high heat input applied to the components, the component experience tensile residual stress. In [39] also agreed to the statement, but they mention that heat input just has little influence to the welding residual stress.

Table-2. Residual stress distribution based on steel and electrode [40].

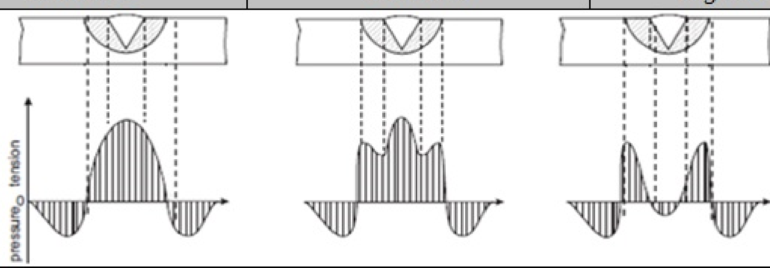
Steel	Austenitic	S690QL (StE 70)	S690QL (StE 70)
Electrode	Austenitic	Austenitic	High-strength
Welding residual stress distribution			

Table-3. Residual stress distribution on types of welding sequence.

Welding Sequence	Residual Stress Part	Tensile Residual Stress	Compressive Residual Stress
Single-pass butt-welded	Longitudinal	Near the weld	Far the weld
	Transverse	Middle of plate	End of the weld
Multi-pass butt welded	Longitudinal	Near the weld bead along the weld line	Far from the weld line
	Transverse	Upper surface of the plate	Bottom plate surface
Circular patch welds	Circumferential	Patches central region and HAZ	Far from the weld bead and HAZ
	Radial	Patches central region	-

Welding sequence

In [41] compare the effect of welding sequence on residual stress in thin-walled octagonal pipe-plate structure. They found that welding sequence has less effect on residual stress. Tensile residual stress exists at both outer an inner surface of the longitudinal residual stress same for all welding sequences. But, the welding sequence does influence the distribution of transverse residual stress for the inner surface of the pipe. They suggest to choose 8-seg-d welding sequence to obtain smaller residual stress. According to [42], the pipe components inner surface stress can be manipulated by changing the weld sequence. This technique can be used in controlling stress distributions prevent welding cracking. In [43] found that welding sequence influence residual stress distribution near the weld of pipe welding.

Table-3 shows the results from [44] which compare the effects of welding sequence on residual stress based on the type of welding sequence. Tensile residual stress mostly located in weld zone of SAE 1020 plate material. They found tensile residual stress at HAZ. They also found compressive residual stress exist in their study, but the stress distribution is too general. This show that different type of welding sequence influence the residual stress distribution. They also suggest some suitable welding sequence, which gives the small measurement of residual stress. The suggestion is used symmetric welding for single-pass welds, use case (A) welding sequence in multi-pass welds and apply back step welding for smaller residual stress for circular patch welds.

Usually, weld zone especially at the center experience the tensile residual stress. But, there are some researchers found there the compressive residual stress also occur at weld zone. They also agreed that residual stress exists at the HAZ, but the distribution still confusing. From the research, it can be concluded that there is residual stress exist in welding component. But, the stress is not focusing on one type of stress where it consists both stresses in different location or parts. Due to the complex stress distribution, more research need to be done to find the specific residual stress respect to a specific location with the specific treatment or welding parameter. To obtain better quality and beneficial residual stress, there are some points that welder needs to know before start welding:

- Material specification (base and filler material)
- Welding parameter, especially heat input
- Welding process
- Welding sequence

Measurement

There are many methods in measure residual stress such as x-ray, hole drilling, sectioning techniques and others. But, most appropriate technique for residual stress measurement depends primarily upon the scale or type of residual stress whether the stress from type I, type II or type III. There is no single method is capable of measuring all the stress type. Different methods give different results so for the best results, better to choose a suitable method depend on the stress type. There are many methods in measure residual stress. The method can be classified into three types which are nondestructive, semi destructive and destructive.

- Nondestructive: X-ray, neutron and synchrotron diffraction; ultrasonic method; and Barkhausen noise method.
- Semi destructive: Hole-drilling, ring-core and deep-hole methods
- Destructive: Sectioning compliance techniques and contour method.

Based on [10] mention that residual stress measurement can be chosen according to their nature residual stress. For the residual stress arise from macro stress can be measured by mechanical method (e.g.: ring-core technique and hole drilling technique), while x-ray and neutron diffraction methods are suitable for residual stress distribution. Measurement or residual stress that exists from the effect on distinct physical properties can be determined by using ultrasonic and magnetic methods. It suggests some method in identifying residual stress based on a residual stress scale, as shown in Table-4.

Table-4. Method in measuring residual stress based on its scale.

Method	Method Type	Residual Stress Scale
Mechanical	Destructive	Type I
X-ray diffraction	Non-destructive (surface)	Type I and II
Neutron diffraction	Non-destructive	Type I and II
Ultrasonic	Non-destructive	Type I , II and III
Magnetic	Non-destructive	Type I , II and III

Nowadays, researchers prefer to use nondestructive method, especially x-ray diffraction [29] and neutron diffraction [17] method in determining welding residual stress. Recently, researchers have chosen finite element method as residual stress identification method [45, 46]. Finite element method (FEM) is a numerical procedure that use integral formulation in solving numerous engineering problems such as the residual stress [47]. But, this FEM in welding processes are complex and computationally expensive [48]. Because of that, according to [49], there are 75% of companies and academics prefer to use an XRD method in measuring residual stress. This is because the XRD method is fast, can be repeatable, harmless to the specimen, and can control the specimen quality. There are some points need to be considered before choosing residual stress measurement method such as:

- Specimen: For high cost, rare and small specimen size better uses nondestructive method
- Feasibility of machine/method: Less cost, easy to handle, less technology, less analysis choose destructive method
- Residual stress type: Type I, II or III (refer to Table-4)
- Research objective: For residual distribution objective choose either x-ray and neutron diffraction methods [10].

Heat treatment

Heat treatment is any treatment that used to improve the characteristics of material or regain those characteristics that affected by welding process [50]. It also can be identified as operations that involves the heating and cooling of material at specific rate or location for the purpose of obtaining certain desirable properties especially in physical, mechanical, magnetic or electrical aspect [51, 52]. Welding is a process of heating and cooling rapidly that cause harder heat affected zone, residual stress and cold cracking. Preheating and post weld heat treatment are the primary means to solve this problems [53]. There are many techniques or procedure in relief residual stress. In [54] mention that residual stress can be reduced or eliminated by stretching and also by applying thermal treatments such as stress relieving or

ARPN Journal of Engineering and Applied Sciences

annealing. Shoot peening and pre-stressing can enhance components resistance against damage [3].

Preheat is a process of heating base metal either in its entirety or just the region surrounding the joint to a specific desired temperature which use for slow down cooling rate, reduce shrinkage stress, promote fusion and also remove moisture [55]. While, post weld heat treatment (PWHT) or also called stress relief is a method for reducing and redistributing the residual stress in the material that have been introduced by welding. PWHT is any heat treatment after welding that used to improve the properties of weld components and it can be many different method or treatments [56]. Advantages by applying PWHT other than reduce residual stress are it can prevent brittle fracture, soften the components hardened zone and make the machining process easy [57]. According to [58], PWHT showed highest fracture toughness compared to as welded components and it was the most commonly used treatment for the welded joints. In [17] research state that there are significant differences in residual stress between as-welded and PWHT components. It found that there is compressive stress were found in the weld metal while tensile residual stress near the outer boundary of the HAZ, and towards the weld root region in both as-welded and post heat treatment. According to [15] state that heat treatment can cause failure, fracture and stress corrosion cracking. This show that certain treatment does not have significant changes to the component. It is also believed that some tensile residual stresses remain after PWHT, but it still can control the residual stress level [59].

Residual stress is one unique characteristic because it can give positive and negative effect to the components. If the components gave the positive effect it will increase the components life span and improve the component quality. But, if the components experience the negative effect (tensile residual stress), the components can undergo some process or activities to induce compressive residual stress to balance the stress so it can be in normal or in compressive residual stress state. In [60] mention that the compressive stress that induced by the post weld treatment can modify the tensile residual stress. Choosing the right method is important because if the existence stress and the applied stress (stress from PWHT) is a tensile stress type, it will increase the stress and can cause the components become worse. So, it is important to know the residual stress type that exists in welds components before applying PWHT. It is because it can increase or decrease the existing stress.

3. EFFECT OF RESIDUAL STRESS

Residual stress gives both positive and negative effects to welding component, usually the compressive residual stress lead to positive or beneficial effect to the components. Researchers found that residual can prevent origination and propagation of fatigue cracks, increase corrosion resistance [5, 13], increase life time of weld components [61] and prevent stress corrosion cracking failures [12].

Mostly, the residual stress cause more on the negative than the positive effect to welding component and the negative effect is tensile residual stress. In [16] found that residual stress can reduce buckling strength, brittle fracture strength, fatigue life strength and cause stress corrosion and hydrogen cracking in welding components [5, 8, 41]. Residual stress also affected the prediction of brittle fracture and affect the lifetime prediction of components. In 2012, there are helicopters accident due to the residual stresses that introduced during the welding operation, were not fully taken into account during the design of the shaft [62]. This show that residual stress important in predicting components life time and reduce component destruction.

4. RESIDUAL STRESS APPLICATION

Even though residual stress could be detrimentally or favorably to components, but the existence give new point in components lifetime prediction. By identifying the residual stress, whether it compressive or tensile residual stress the technician can predict the actual lifetime of a component. In [63] state that residual stress data is important to obtain the accurate fatigue lifetimes of components. By applying the knowledge of residual stress micro cage had been created. In [64, 65] state that micro cage have the potential for use in biological and biomedical applications such as biopsy of cancerous tumors or capture and manipulation of cells for dissection. The micro cage captures the specimen by trapping the specimen without applying a force. The advantage by using this micro cage is it would not give harm or damage to the specimen. It also can be used to capture, transport and manipulate bio-cells for dissection and injection.

5. CONCLUSIONS

Residual stress is one of the displacement controlled stress (secondary stress). Residual stress is a residue or remaining stress in a component that arise from either thermal or mechanical method after all external load are removed. The effect of this residual stress may be positive or negative depend on its type, whether it tensile residual stress or compressive residual stress. There are many activities or processes that can cause residual stress, usually surface treatments (shoot peening and grinding) which give the compressive residual stress to components. It can retard initiation and growth of fatigue cracks. The metallurgical process (welding) can give both tensile and compressive residual stress to component, but it gives different stress at different location especially in welding components.

In welding components majority of the researchers agreed that weld zone, especially at the center experience the tensile residual stress. But, the residual stress distribution that exist at the HAZ still confusing and complex [31]. In [16] found that there is compressive residual stress at HAZ can be specific found at CGHAZ (coarse grain heat affected zone), but other HAZ parts still unknown. Usually, residual stress causes cracks to components. If welding components suffer from certain quality defect, repair welding is not the conclusion because it can introduce high residual stress to the repair region [66].

Due to that, stress relief (heat treatment) introduced to reduce residual stress to improve the negative residual stress. By applying the PWHT to the components, welder or engineer can increase the component lifetime and can improve its quality. But, both process repair welding and heat treatment are time consuming and costly [67, 68]. By using the welding residual stress distribution data, the welder can choose the right welding treatment that produces components with low residual stress, less and specific location for heat treatment and without repair welding process. So, it is important to know the welding residual stress distribution because it can cut or reduce the time and cost production. There are some suggestions for future works:

- Distribution of residual stress at HAZ in term of type and its location.
- Effect of welding residual stress to HAZ microstructure.
- Effect of residual stress to the variant selection at HAZ

By gathering the information, engineer or welder can improve the weld components, increase the components life time and reduce the maintenance.

ACKNOWLEDGEMENT

This research project is fully supported by the Short Term Research Grant awarded by University Malaysia Kelantan with grant number: R/SGJP/A08.00/00896A/001/2014/000160.

REFERENCES

[1] NDT Resource Center. Stress and strain. https://www.nde-ed.org/EducationResources/CommunityCollege/Materials/Mechanical/StressStrain.htm.

[2] P. J. Withers, M. Turski L. Edwards, P. J. Bouchard and D. J. Buttle. 2008. Recent advances in residual stress measurement. International Journal of Pressure Vessels and Piping. 85(3): 118-127.

[3] G. H. B. Donato and R. Magnabosco. 2014. Modeling and characterization of residual stresses in material processing. Comprehensive Materials Processing: Materials Modeling and Characterization. 2: 219-233.

[4] P. J. Withers and H. K. D. H. Bhadeshia. 2001. Residual stress: Part 1-Measurement techniques. Materials Science and Technology. 17(4): 355-365.

[5] N. S. Rossini, M. Dassisti, K. Y. Benyounis and A. G. Olabi. 2012. Methods of measuring residual stresses in components. Materials and Design. 35: 572-588.

[6] J. A. Francis, H. K. D. H. Bhadeshia and P. J. Withers. 2007. Welding residual stresses in ferritic power plant steels. Materials Science and Technology. 23(9): 1009-1020.

[7] Reddy A. V. 2004. Investigation of aeronautical and engineering component failures. CRC Press. Florida, US.

[8] James M. N. 2010. Residual stress influences in mechanical engineering. In: XVIII Congreso Nacional de Ingeniería Mecánica. pp. 1-13.

[9] P. J. Withers and H. K. D. H. Bhadeshia. 2001. Residual stress: Part 2-Nature and origins. Materials Science and Technology. 17(4): 366-375.

[10] Macherauch E. 2014. Introduction to residual stress. In: Advances in Surface Treatments: Technology-applications-effects. A. Niku-Lari (Ed.). pp. 1-36.

[11] Totten G. E. 2007. Steel heat treatment handbook. 2nd Ed. CRC Press. Florida, US.

[12] B. Ahmad and M. E. Fitzpatrick. 2015. Surface preparation for residual stress measurement of an accelerated corrosion tested welded marine steel. Corrosion Science. 91: 357-360.

[13] D. J. Buchanan and R. John. 2014. Residual stress redistribution in shot peened samples subject to mechanical loading. Materials Science & Engineering: A. 615: 70-78.

[14] Gür C. H. and Savas S. 2012. Measuring the surface residual stresses in shot peened steel components by magnetic barkhausen noise method. In: 18th World Conference on Nondestructive Testing. pp. 1-7.

[15] C. J. Lammi and D. A. Lados. 2012. Effects of processing residual stresses on fatigue crack growth behavior of structural materials: experimental approaches and microstructural mechanisms. Metallurgical and Materials Transactions A. 43(1): 87-107.

[16] J. B. Ju, J. S. Lee, J. I. Jang, W. S. Kim and D. Kwon. 2003. Determination of welding residual stress distribution in API X65 pipeline using a modified magnetic Barkhausen noise method. International Journal of Pressure Vessels and Piping. 80(9): 641-646.

[17] S. Paddea, J. A. Francis, A. M. Paradowska, P. J. Bouchard and I. A. Shibli. 2012. Residual stress

distributions in a P91 steel-pipe girth weld before and after post weld heat treatment. Materials Science and Engineering: A. 534: 663-672.

[18] Fergani O., Shao Y., Lazoglu I. and Liang S. Y. 2014. Temperature effects on grinding residual stress. Procedia CIRP. 14: 2-6.

[19] Fitzpatrick M. E., Fry A. T., Holdway P., Kandil F. A., Shackleton J. and Suominen L. 2005. Determination of residual stresses by X-ray diffraction. National Physical Laboratory. Teddington, UK.

[20] American Welding Society. 1999. Vision for welding industry (final technical report). https://app.aws.org/research/vision.pdf.

[21] Jeffus L. 2012. Chapter 1: Introduction to welding. In: Welding Principle and Application. Delmar Cengage Learning. New York, US. pp. 4-23.

[22] Callister W. D. 2001. Fundamentals of materials science and engineering. 5th Ed. John Wiley & Sons Inc. New York, US.

[23] Callister W. D. 2007. Materials science and engineering-An introduction. 7th Ed. John Wiley & Sons Inc. New York, US.

[24] C. Balasingh and A. K. Singh. 2000. Residual Stresses and their measurements by x-ray diffraction methods. Metals Materids and Processes. 12(2 & 3): 269-280.

[25] J. T. Assis, V. Monin, J. R. Teodosio and T. Gurova. 2002. X-ray analysis of residual stress distribution in weld region. Advances in X-ray Analysis. 45: 225-231.

[26] R. H. Leggatt. 2008. Residual stresses in welded structures. International Journal of Pressure Vessels and Piping. 85(3): 144-151.

[27] T. Kannengiesser and A. Kromm. 2009. Formation of welding residual stresses in low transformation temperature (LTT) materials. Soldagem & Inspeção. 14(1): 74-81.

[28] K. C. Wu. 1981. Residual stress measurements in repair-welded titanium sheets. Welding Journal. 60(1): 12-18.

[29] V. I. Monin, T. Gurova, X. Castello and S. F. Estefen. 2009. Analysis of residual stress state in welded steel plates by X-ray diffraction method. Reviews on Advanced Materials Science. 19: 172-175.

[30] Vemanaboina H., Akella S. and Buddu R. K. 2014. Welding process simulation model for temperature and residual stress analysis. Procedia Materials Science. 6: 1539-1546.

[31] G Bussu and P. E. Irving. 2003. The role of residual stress and heat affected zone properties on fatigue crack propagation in friction stir welded 2024-T351 aluminium joints. International Journal of Fatigue. 25(1): 77-88.

[32] G. Pouget and A. P. Reynolds. 2008. Residual stress and microstructure effects on fatigue crack growth in AA2050 friction stir welds. International Journal of Fatigue. 30(3): 463-472.

[33] D. Deng. 2009. FEM prediction of welding residual stress and distortion in carbon steel considering phase transformation effects. Materials and Design. 30(2): 359-366.

[34] C. Liu, J. X. Zhang and C. B. Xue. 2011. Numerical investigation on residual stress distribution and evolution during multipass narrow gap welding of thick-walled stainless steel pipes. Fusion Engineering and Design. 86(4): 288-295.

A. Yaghi, T. H. Hyde, A. A. Becker, W. Sun and J. A. Williams. 2006. Residual stress simulation in thin and thick-walled stainless steel pipe welds including pipe diameter effects. International Journal of Pressure Vessels and Piping. 83(11): 864-874.

[35] P. Vasantharaja, M. Vasudevan and P. Palanichamy. 2014. Effect of welding processes on the residual stress and distortion in type 316LN stainless steel weld joints. Journal of Manufacturing Processes. 19: 187-193.

[36] Tall L. 1962. Heat input thermal and residual stresses in welded structural plates. Lehigh University, Pennsylvania, US.

[37] [A. M. Paradowska, J. W. H. Price, R. Ibrahim and T. R. F. Layson. 2006. The effect of heat input on residual stress distribution of steel welds measured by newtron diffraction. Journal of Achievements in Material and Manufacturing Engineering. 17(1-2): 385-388.

[38] S. Xu, R. Wei, W. Wang and X. Chen. 2014. Residual stresses in the welding joint of the nozzle-to-head area of a layered high-pressure hydrogen storage tank. International Journal of Hydrogen Energy. 39(21): 11061-11070.

[39] ISF Welding and Joining Institute. 2011. Residual stresses. http://mercury.kau.ac.kr/welding/Welding%20Techno

logy%20II%20-%20Welding%20Metallurgy/Chapter%203%20-%20Residual%20Stresses.pdf.

[40] D. F. Fu, C. Q. Zhou, L. I. Can, W. A. N. G. Guan and L. X. Li. 2014. Effect of welding sequence on residual stress in thin-walled octagonal pipe-plate structure. Transactions of Nonferrous Metals Society of China. 24(3): 657-664.

[41] Yang Y. P., Babu S. S., Kikel J. M. and Brust F. W. 2011. Investigation of weld crack mitigation techniques with advanced numerical modeling and experiment-Summary. In: Hot Cracking Phenomena in Welds III. J. Lippold, T. Böllinghaus and C. E. Cross (Eds.). pp. 353-365.

[42] C. H. Lee and K. H. Chang. 2009. Effect of the welding sequence in the circumferential direction on residual stress distribution in a thin-walled pipe weld. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture. 223(6): 723-735.

[43] T. L. Teng, P. H. Chang and W. C. Tseng. 2003. Effect of welding sequences on residual stresses. Computers and Structures. 81(5): 273-286.

A. Ravisankar, S. K. Velaga, G. Rajput and S. Venugopal. 2014. Influence of welding speed and power on residual stress during gas tungsten arc welding (GTAW) of thin sections with constant heat input: A study using numerical simulation and experimental validation. Journal of Manufacturing Processes. 16(2): 200-211.

[44] L. Zhao, J. Liang, Q. Zhong, C. Yang, B. Sun and J. Du. 2014. Numerical simulation on the effect of welding parameters on welding residual stresses in T92/S30432 dissimilar welded pipe. Advances in Engineering Software. 68: 70-79.

[45] Moaveni S. 2003. Finite element analysis: Theory and application with ANSYS. Pearson Education India. Chennai, India.

A. Barroso, J. Cañas, R. Picón, F. París, C. Méndez and I. Unanue. 2010. Prediction of welding residual stresses and displacements by simplified models: Experimental validation. Materials and Design. 31(3): 1338-1349.

[46] O. S. Zaroog, C. Y. W. Ken and A. N. A. Manap. 2014. Current and Challenge of residual stress measurement techniques. International Journal of Science and Research. 3(9): 210-216.

[47] Gillissie J. G. Heat treatment-What is it?. 1981. http://www.nationalboard.org/Index.aspx?pageID=177.

[48] Digges T. G., Rosenberg S. J. and Geil G. W. 1966. Heat treatment and properties of iron and steel. National Bureau of Standards Monograph 88. Washington D.C., US.

[49] Manna R. 2012. Heat treatment. http://www.msm.cam.ac.uk/phase-trans/2012/Manna/Part1.pdf.

[50] B. K. Srivastava, S. P. Tewari and J. A. Prakash. 2010. Review on effect of preheating and/or post weld heat treatmemt (PWHT) on mechanical behaviour of ferrous metals. International Journal of Engineering Science and Technology. 2(4): 625-631.

[51] Kalpakjian S., Schmid S. R. and Kok C. W. 2008. Manufacturing processes for engineering materials. 5th Ed. Prentice Hall. New Jersey, US.

[52] J. Quere. 1996. European federation for welding, joining and cutting. LASTECHNIEK, 62: 9-18.

[53] R. S. Funderburk. 1999. Key concepts in welding engineering. Welding Innovation. 16(1): 1-4.

[54] Ahmed K. and Krishnan J. 2003. Post-weld heat treatment-Case studies. BARC Newsletter. 111-115.

[55] S. R. Mohideen and A. M. A. Zaidi. 2011. Influence of post weld heat treatment on the HAZ of low alloy steel weldments. International Journal of Integrated Engineering. 2(1): 7-11.

[56] Trudel A., Brochu M. and Lévesque M. 2013. Residual stress effects on the propagation of fatigue cracks in the weld of a CA6NM stainless steel. In: International Conference on Fracture. 13: 1-10.

[57] X. Cheng, J. W. Fisher, H. J. Prask, T. Gnäupel-Herold, B. T. Yen and S. Roy. 2003. Residual stress modification by post-weld treatment and its beneficial effect on fatigue strength of welded structures. International Journal of Fatigue. 25(9-11): 1259-1269.

[58] J. Perenda, J. Trajkovski, A. Žerovnik and I. Prebil. 2015. Residual stresses after deep rolling of a torsion bar made from high strength steel. Journal of Materials Processing Technology. 218: 89-98.

[59] GOV.UK. 2012. Aircraft accident report AAR 2/2014-Eurocopter EC225 LP Super Puma, G-REDW and Eurocopter EC225 LP Super Puma, G-CHCN, 22 October 2012. https://www.gov.uk/aaib-reports/aar-2-2014-g-redw-and-g-chcn-10-may-2012.

ARPN Journal of Engineering and Applied Sciences

[60] G. A. Webster and A. N. Ezeilo. 2001. Residual stress distributions and their influence on fatigue lifetimes. International Journal of Fatigue. 23: 375-383.

[61] J. K. Luo, R. Huang, J. H. He, Y. Q. Fu, A. J. Flewitt, S. M. Spearing, N. A. Fleck and W. I. Milne. 2006. Modelling and fabrication of low operation temperature microcages with a polymer/metal/DLC trilayer structure. Sensors and Actuators A: Physical. 132(1): 346-353.

[62] Y. Q. Fu, J. K. Luo, A. J. Flewitt, S. E. Ong, S. Zhang, H. J. Du and W. I. Milne. 2007. Microactuators of free-standing TiNiCu film. Smart Materials and Structures. 16(6): 2651–2657.

[63] Serco Assurance. 2004. Integrity of repaired welds (phase 1)-Deliverable 5 summary report. Health and Safety Executive. http://www.hse.gov.uk/research/rrpdf/rr191.pdf.

[64] The Welding Institute. 2016. Heat treatment of welded joints-Job knowledge 114. http://www.twi-global.com/technical-knowledge/job-knowledge/heat-treatment-of-welded-joints-part-1-114/.

[65] Zhili F. 2005. Processes and mechanisms of welding residual stress and distortion. Woodhead Publishing Limited. Cambridge, England.