A Critical Review on Residual Stresses in Welded Joints

Renuka Nethi[1] V. Ramalingeswara Rao[2] Naresh Mamidi[3] Addetla Girish Kumar[4]
[1,3,4]M.Tech Student [2]Associate Professor
[1,2,3,4]Department of Mechanical Engineering
[1,2,3,4]Vidya Jyothi Institute of Technology, Aziz Nagar, Hyderabad, India

Abstract— Residual stresses are secondary stresses exist after all loads are removed. Residual stresses can be favorable or detrimental to some components, depending on the type of material. Usually, tensile residual stress can cause harm to components while compressive residual stress can improve the component quality. Residual stresses, either tensile or compressive are present in almost all manufactured components. 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 of welding residual stress varies in different locations depending on welding parameters, types, sequence, component type, component materials and component sizes. Residual stress in weldments is one of the major concerns in manufacturing industries. They occur, sometimes during the initial processing of metals and sometimes during rolling, forging, casting etc. In welding these stresses develop due to non-uniform cooling of the welded zone. Tensile stresses are primarily responsible for crack initiation and product failure. Residual stress may also lead to premature failure of the welded joints when subjected to hazardous conditions. There are various physical methods of detection of residual stress in weldments such as x-ray diffraction and deep- hole- drilling. Nevertheless, numerical, is also one of the most popular methods among researchers to solve various complex engineering problems. The current review aims at discussing the types, causes and effects of residual stresses in welded joints. The scope of the review also includes discussing different residual stress measuring methods.

Key words: Residual Stresses, Residual Stresses in Welding, X-Ray Diffraction Method, Weldments

I. 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. 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 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 exists within components due to imposed displacement without any external applied loads [1].

Residual stresses and distortions can cause major problems in the welded structures. Residual stresses are produced in the weldment due to mismatching and non-uniform distributions of plastic and thermal strains. As the temperature of the base metal increases, the yield strength decreases and the thermal stress increases. The mismatching (in the weld in general) occurs due to joint geometry and plate thickness. Welding procedures and degree of restraints are also influences the residual stress distributions. Within the fusion zone, the heat affected zone (HAZ) and the adjacent parent material where the thermal softening and thermal strains caused by the heat flow from the weld are sufficient to cause yielding during welding, the residual stress field will be dominated by the weld-induced residual stresses. At greater distances from the weld, the residual stresses after welding will be a function of the superimposition of the weld-induced residual stresses and any pre-existing residual stresses in the parts being joined. This superimposition may be in the linear elastic or nonlinear elastic plastic or creep range. In large steel fabrication industries such as shipbuilding, marine structures, aero-space industry, high speed train guide ways and pressure vessels and piping in chemical and petrochemical industry the problem of residual stresses and overall distortion has been and continue to be a major issue. During welding a very complex thermal cycle is applied to the weldment which in turn causes irreversible elastic-plastic deformation and consequently gives rise to the residual stresses in and around fusion zone and heat affected zone (HAZ)[1].

II. Residual Stresses

Residual stress is the stress that exist within a component when there is no external load are applied to it Residual stresses are also called as locked-in stresses, can be defined as those stresses existing within a body in the absence of external loading or thermal gradients. In other words, residual stresses in a structural material or component are those stresses which exist in the object without the application of other external loads or any service. Residual stress may be desirable or undesirable. Residual stress is the stress that exist within a component when there are no external loads are applied to it. In other words, residual stress is the stress that remain within a material or a 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. So, any remaining or residual stresses that exists in a component either in thermal or mechanical method without any applied external loads can be identified as residual stress[2].

Olabi et al in their paper stated that residual stresses are stresses that remain in a solid material after the original cause of the stresses has been removed. Residual stress may be desirable or undesirable. Residual stresses can occur through a variety of mechanisms including inelastic (plastic) deformations, temperature gradients (during thermal cycle) or structural changes (phase transformation) [3].

Tso – Liang stated in their experiment that heat from welding may cause localized expansion, which is taken up during welding by either the molten metal or the placement of parts being welded. When the finished weldment cools, some areas cool and contract more than others, leaving residual stress.[3]

III. TYPES OF RESIDUAL STRESSES

Residual stresses are spontaneously in equilibrium as tensile residual stresses which are known as detrimental and compressive residual stresses which are known as beneficial. For example, a surface formed in tensile stresses will comprise compressive residual stresses, and a surface formed in compressive stresses will contain tensile residual stresses. 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[4].

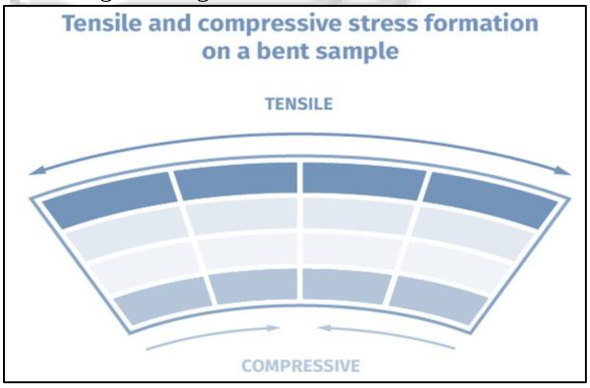

Fig. 1: Tensile & Compressive Stress Formation on Bent Sample

A. Tensile Residual Stresses

This stresses are decrease the fatigue strength and cause fatigue failure. Tensile residual stresses are usually the side effects of production such as in aggressive grinding which causes crack growth. They can also be remaining tensions as residual stresses which may cause cracking on the component surface. In addition, stress corrosion cracking is a phenomenon which occurs in the presence of tensile residual stresses. Operation such as welding, machining, grinding and rod or wire drawing can cause harm and can give tensile residual stress to components. The tensile residual stresses are not preferred in any specimen because of its effective in fatigue life under dynamic loading, crack initiation and propagation and corrosion, which lead to failure. After welding, a non-uniform temperature distribution for the welded zone introduces the tensile residual stresses, it can have a dangerous effect on the material by reducing the fatigue life of metal, crack propagation, brittle fracture and stress corrosion[5].

B. Compressive Residual Stresses

This stresses are increases both the fatigue strength and resistance to stress corrosion cracking. They are of inducing compressive residual stresses is to balance the detrimental effects of tensile stresses. One of the heat treatment processes, stress-relief annealing, can also be used to reduce the residual tensile stresses. While surface treatments such as shoot peening give the compressive residual stress, which can enhance performance for components. Most of the surface treatments can induce compressive residual stress, but if it had been done in the right way. Mostly, metallurgical process such as heat treatment and welding introduce compressive residual stress to components. The beneficial effect of compressive stresses have been widely used in industry as these are believed to increase fatigue strength of the component and reduce stress corrosion cracking and brittle fracture[6].

IV. 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 increase life time of weld components and prevent stress corrosion cracking failures. Mostly, the residual stress cause more on the negative than the positive effect to welding component and the negative effect is tensile residual stress. residual stress can reduce buckling strength, brittle fracture strength, fatigue life strength and cause stress corrosion and hydrogen cracking in welding components. 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. This show that residual stress important in predicting components life time and reduce component destruction[7].

V. FACTORS THAT CAUSE RESIDUAL STRESSES

– Residual stresses can be present in any mechanical structure because of many causes. Residual stresses may be due to the technological process used to make the component.
– Manufacturing processes are the most common causes of residual stress.
– Virtually all manufacturing and fabricating processes such as casting, welding, machining, molding, heat treatment, plastic deformation during bending, rolling or

forging introduce residual stresses into the manufactured object.

- Residual stress could be caused by localized yielding of the material, because of a sharp notch or from certain surface treatments like shot peening or surface hardening.
- Among the factors that are known to cause residual stresses are the development of deformation gradients in various sections of the piece by the development of thermal gradients, volumetric changes arising during solidification or from solid state transformations, and from differences in the coefficient of thermal expansion in pieces made from different materials.
- Thermal residual stresses are primarily due to differential expansion when a metal is heated or cooled.
- The two factors that control this are thermal treatment (heating or cooling) and restraint. Both the thermal treatment and restraint of the component must be present to generate residual stresses.
- When any object is formed through cold working, there is the possibility for the development of residual stresses[8].

VI. ROLE OF RESIDUAL STRESSES

Residual stresses have the same role in a structure's strength as common mechanical stresses. However, while stress due to external loads can be calculated with a degree of accuracy, residual stresses are difficult to foresee.

It is, therefore, very important to have a reliable method able to measure them directly with minimum damage to the surface.

Residual stresses can play a significant role in explaining or preventing failure of a component at times.

One example of residual stresses preventing failure is the shot peening of component to induce surface compressive stresses that improve the fatigue life of the component [9].

VII. RESIDUAL STRESS MEASURING METHODS

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 of method. 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.

- X-Ray Diffraction

The most common technique is a special type of XRD test which is used for measuring the stresses in fine grained crystalline materials x-ray diffraction and neutron diffraction methods are suitable for residual stress distribution. The measurements of the XRD tests of the stress relieved specimens showed that theses tensile residual stresses are greatly reduced to a minimum level[10].

- Ultrasonic Methods

Residual stress that exists from the effect on distinct physical properties can be determined by using ultrasonic method.

- Magnetic Methods

Residual stress that exists from the effect on distinct physical properties can be determined by using Magnetic method.

- Electronic Speckle Pattern Interferometry.
- Hole Drilling and Strain Gage Technique

For the residual stress arise from macro stress can be measured by mechanical method (e.g.: ring core technique and whole drilling technique). This hole drilling method, is employed only when the X-ray technique is not helpful.

A. X-Ray Diffraction Method

Neubert et al discussed the effects of non-uniform martensitic transformation and subsequently leading to the formation of residual stress. They also developed a numerical method to determine the residual stress and compared the results obtained by using X-ray diffraction method and numerical method. The material that is chosen is low alloyed high strength steel as base material and super-martensitic high alloyed filler material[3].

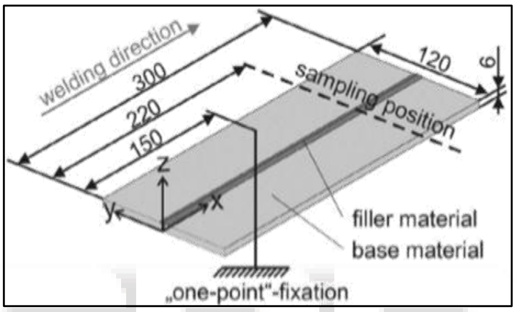

Fig. 2: X-Ray Diffraction Method

Nowadays, researchers prefer to use nondestructive method, especially x-ray diffraction and neutron diffraction method in determining welding residual stress. Recently, researchers have chosen finite element method as residual stress identification method. Finite element method (FEM) is a numerical procedure that use integral formulation in solving numerous engineering problems such as the residual stress but, this FEM in welding processes are complex and computationally expensive Because of that, according to 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. After shot peening, the induced residual stresses were measured by the XRD tests, and the outputs exhibited the complete elimination of the tensile residual stresses and formation of compressive residual stresses instead. 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 chooses destructive method.

- Residual Stress Type

Macro residual, micro residual stress, atomic-scale stress.

- Research Objective

For residual distribution objective choose either x-ray and neutron diffraction methods [11].

B. Ultrasonic Method

Bray et al in their experiment used a linear relationship between the velocity of ultrasonic wave and the stress of material to determine the residual stress. This relationship, within the elastic limit, is the acoustoelastic effect which gives the time of flight. It is evident that when a longitudinal wave passes through an interface between two materials, there is an incident angle that makes the angle of refraction for the wave 90℃. It can be shown that sensitivity of the LCR waves to the strain is highest amongst the other types of ultrasonic waves. By using the time of flight within the material, the amount of strain can be calculated, since the flight time varies with the amount of strain present. Yashar et al developed a 3-D thermo-mechanical FE analysis to evaluate welding residual stress in austenitic stainless steel pipes. He then compared the results of FE analysis and Ultrasonic method to determine the accuracy of FE analysis[3].

C. Hole Drilling Method

The hole-drilling method is a standard technique for measuring residual stresses. The stress measurements will be made in three points at outer surface of the pipes. These points are made in such a way that point A is located on the weld Centre line, point B 40 mm from the weld Centre line in the stainless-steel side and point C 35 mm in the carbon steel side, Strain gages of type FRS-2-1 will be mounted on the pipe at selected points to measure the released strains after drilling a hole. With the help of the strain value, stress can be found since these are inversely proportional. The hole is made by using a very high-speed drill of RS-200 type[3].

Fig. 3: Experimental Setup of Hole Drilling Method

Akbari et al used the finite element techniques to analysis the thermo-mechanical behavior and residual stresses in dissimilar butt-welded pipes. The residual stresses at the surface of some weld specimens were measured experimentally by using the hole-drilling method. The results of the finite element analysis were compared with experimentally measured data to determine the accuracy of the finite element modelling. Based on this study, a modelling procedure with reasonable accuracy was developed[3].

VIII. Residual Stress Application

Even though residual stress could be detrimentally or favorably to components, but the existence gives 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. 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. Micro cage has 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[8].

IX. Residual Stress in Weldments

Residual stress in any material arises from the day it is processed from ingot to the final form. It is generated during rolling, forging, casting etc. Residual stresses would be set up when a component is stressed beyond the elastic limit and when plastic flow occurs. In welding, it would usually be at a macro level. Uneven cooling and heating in the weldment are the major cause of residual stresses in weldment. There is a homogeneous volume change due to local heating and cooling which leads to the building up of elastic stress. To be more precise the various sources of residual stress in weldment would be due to

- Shrinkage process of the seam and HAZ.
- More rapid cooling of the surface.
- Phase transformation.
- Superimposition of residual stress owing to shrinkage, quenching and transformation[12].

A. Welding Residual Stress

Welding is one of the most important joining process, especially for large scale structures, and has been widely used in many industries like automobile, ship, airplane and so on. 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. Welding is a joining process of two or more metal parts to form a single product 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[13].

Different researchers have discussed on effect of various welding parameters on mechanical strength of butt weld joint in various ways. They are summarized below.

Dr. T. Srihari. al. carried out the effect on groove angle on angular distortion and impact strength butt welds and concluded that the importance of groove angle, also conclude that distortion has been increased with increase in the groove angle till 600.

N. Ren et. al. studied the constraining effects of the weld and heat-affected zone (HAZ) material in welded tube numerical control (NC) bending process are key problem to be solved in the research, development and application of thin-walled welded tubes. The constraining effects of the weld and HAZ material in welded tube NC bending process are obtained by using FE simulation. The results are shown as follows:

1. As the weld line locates on the outside, the constraining effects of the weld and HAZ material make the tangent strain and thickness strain decrease, the hoop strain increase in weld and HAZ 2. As the weld line locates on the outside, the larger constraining effect of the weld makes the wall thinning at the outside crest line decrease greatly as compared with the model-PA, while the HAZ material has little constraining effect on the wall thinning. The constraining effects of the weld and HAZ material become larger as the weld line locates on the outside and inside[14].

B. *Tig Welding*

Gas-tungsten arc welding (GTAW) is a process that melts and joins metals by heating them with an arc established between a non-consumable tungsten electrode and the metals. The tungsten electrode is normally contacted with a water cooled copper tube, which is connected to the welding cable to prevent overheating. The shielding gas (Ar, He) goes through the torch body and nozzle toward the weld pool to protect it from air. Filler metal (for joining of thicker materials) can be fed manually or automatically to the arc. It is also called tungsten inert gas (TIG) welding. ELECTRODES: Tungsten electrodes with 2% cerium or thorium give better electron emissivity, current-carrying capacity, and resistance to contamination than pure electrodes. Hence, the arc is more stable. SHIELDING GASES: Ar is heavier and offers more effective shielding and cheaper than He.[15]

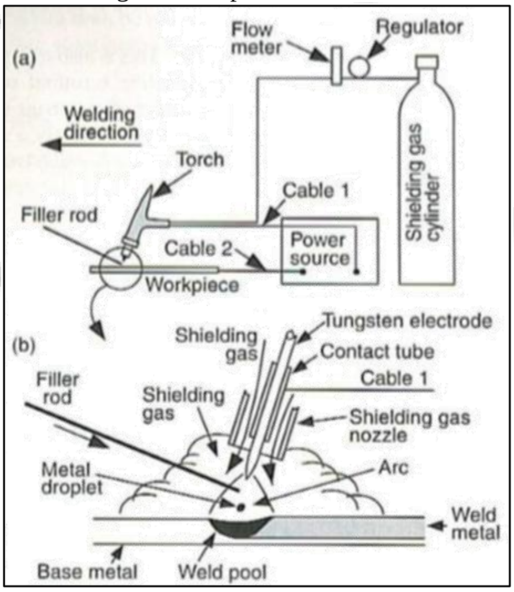

Fig. 4: Tungsten Inert Gas Welding

X. DISTRIBUTION OF RESIDUAL STRESSES

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

1) The existence of residual stress before welding (manufacture and fabrication)
2) Material properties (weld and parent metal)
3) The geometry of the joined components
4) Restrain applied
5) Welding procedure
6) Operation after welding

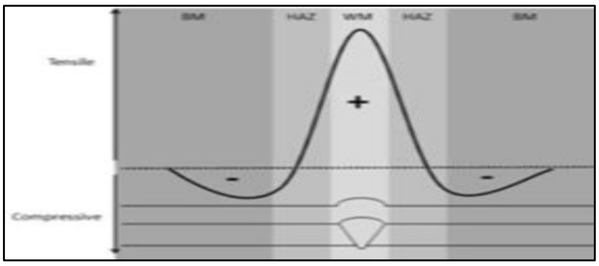

Fig. 5: Welding Residual Stress Distribution

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 exists 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 [13].

XI. CONCLUSION

Residual stress in weldments is one of the major concerns in manufacturing industries. The distribution of welding residual stress varies in different locations depending on welding parameters, types, sequence, component type, component materials and component sizes. They occur, sometimes during the initial processing of metals and sometimes during rolling, forging, casting etc. In welding, these stresses develop due to non-uniform cooling of the welded zone. Tensile stresses are primarily responsible for crack initiation and product failure. Residual stress may also lead to premature failure of the welded joints when subjected to hazardous conditions. There are various physical methods of detection of residual stress in weldments such as x-ray diffraction and deep- hole- drilling. Numerical method, is also one of the most popular methods among researchers to solve various complex engineering problems.

REFERENCES

[1] G. S. Brar and R. Kumar, "PVP2010-25184 FINITE ELEMENT ANALYSIS OF RESIDUAL STRESSES IN BUTT WELDING OF STAINLESS," pp. 3–6, 2018.
[2] N. Nasir, M. Khairul, A. Abdul, U. Sains, and S. Mamat, "Review on Welding Residual Stress," no. June, 2016.
[3] R. Sudhakar, R. J. Raj, P. Jahadeesh, K. Kumaresan, G. Sr, and U. G. Scholars, "Review on Determination of residual stress in Weldments," pp. 951–957, 2017.
[4] X. Lu and T. Hassan, "Residual Stresses in Butt and Socket Welded Joints," no. August, 2001.
[5] A. Kosaki, "Evaluation method of corrosion lifetime of conventional stainless steel canister under oceanic air environment," vol. 238, pp. 1233–1240, 2008.
[6] F. Meng, Z. Lu, T. Shoji, J. Wang, E. hou Han, and W. Ke, "Stress corrosion cracking of uni-directionally cold worked 316NG stainless steel in simulated PWR primary water with various dissolved hydrogen concentrations," Corros. Sci., vol. 53, no. 8, pp. 2558–2565, 2011.

[7] R. K. Khatirkar and S. G. Sapate, “ScienceDirect Effect of heat input on the microstructure , residual stresses and corrosion resistance of 304L austenitic stainless steel weldments,” Mater. Charact., vol. 93, pp. 10–23, 2014.
[8] G. Fu, T. Gurova, M. I. Lourenco, and S. F. Estefen, “Numerical and Experimental Studies of Residual Stresses in Multipass Welding of High Strength Shipbuilding Steel,” J. Sh. Res., vol. 59, no. 3, pp. 133–144, 2015.
[9] I. Facility, S. R. Appleton, H. Oxford, S. E. Eren, S. R. Appleton, and M. Milititsky, “OMAE2013-11192,” pp. 1–16, 2016.
[10] W. U. X. Diffraction, “Residual Stress Characterization of Thick-Plate Weldments Using X-Ray Diffraction,” no. March, pp. 87–91, 1993.
[11] S. Song, P. Dong, and X. Pei, “A Full-Field Residual Stress Estimation Scheme For Fitness-For-Service Assessment Of Pipe Girth Welds : Part I – Identification Of Key Parameters International Journal of Pressure Vessels and Piping A full- fi eld residual stress estimation scheme for fi ,” Int. J. Press. Vessel. Pip., vol. 126–127, no. January, pp. 58–70, 2015.
[12] G. Singh and G. Brar, “PVP2011-57024,” 2017.
[13] N. Syahida, M. Nasir, M. Khairul, A. Abdul, S. Mamat, and M. Iqbal, “REVIEW ON WELDING RESIDUAL STRESS,” vol. 11, no. 9, pp. 6166–6175, 2016.
[14] M. S. Deepali, D. Galhe, and R. M. Burkul, “Ijesrt International Journal of Engineering Sciences & Research Technology a Review Paper on Effect of Welding Speed and Groove Angle on Strength of Butt Weld Joint Using Tig Welding,” vol. 4, no. 5, pp. 425–429, 2015.
[15] J. Kazi, S. Zaid, S. M. Talha, M. Yasir, and D. Akib, “A Review on Various Welding Techniques,” Www.Ijmer.Com, vol. 5, pp. 22–28, 2015.