An assessment of the residual stress field in the HAZ of Tig Welded Aluminium 2219 plates due to weld repairs using High Speed Hole Drilling Technique

By
Jeby Philip and S. Annamala Pillai
Experimental Mechanics Division
Vikram Sarabhai Space Centre
Thiruvananthapuram, PIN- 695 022, Kerala
s_annamala@vssc.gov.in

Abstract

Residual stresses are those stresses, which remain in the material or body in the absence of any external forces or thermal gradients. They are introduced mostly during manufacturing operations like rolling, welding, forming etc. The quantitative estimation of these stresses is important because they can modify the effective load bearing capacity of the component by getting added to the applied or service stresses and also stimulate stress corrosion failures.

Non-destructive evaluation of residual stresses is in general limited to the near surface of the component. The near surface stresses are seen to have sharp gradients. Quantification of the residual stress distribution with depth till the stress values reach their bulk nominal values is important from point of view of the assessment of structural integrity as these stresses can have magnitudes which can be even more than fifty percent of yield stress. Incremental Hole drilling method, which is relatively simple and fast, is one of the most popularly used semi-destructive methods of residual stress evaluation which can provide the residual stress distribution across the thickness in magnitude, direction and sense. The strains relieved by drilling a small hole of approximately 2 mm diameter are measured using special purpose strain gauges and the residual stresses present in the component are computed from the relieved strains.

The paper presents a case study on the stress field in the heat-affected zones (HAZ) of TIG welded 2219 Aluminium plates and also modifications of the stress field by subsequent weld repairs. The representative values in the bulk of the material are also compared. The stress field due to manual weld is also compared to the field in an automatic weld. The near surface residual stresses are analyzed. Relative merits of the hole drilling method over NDT methods are also discussed.

Keywords: residual stress, incremental hole drilling, weld repairs and AA2219 aluminium

Introduction

Present day designs are driven by the concept of efficiency. As the structural designs in aerospace get more complex and at the same time optimal, the margins available are quite low. The designer demands for accurate assessment of operating loads, mechanical properties and other parameters, which can provide information on the adequacy as well as the health of the fabricated component. The presence of residual stress eats into the small structural margins available and hence is one such area, which has been receiving increasing interest. Structural failure can be caused by the combined effect of residual and applied stresses and also in many alloys, the presence of a residual stress field can stimulate stress corrosion. The fact that no manufactured component would be entirely free from residual stresses and also once introduced is difficult to be removed, makes the assessment all the more important.

Residual stresses are self-equilibrating internal stresses existing in a free body which has no external forces or constraints on its boundary [1]. Residual stresses originate from misfits between different regions in a component. These misfits are caused by non-uniform plastic deformations, sharp thermal gradients or chemical action. Residual stresses are categorized by cause, by the scale over which they self equilibrate or according to the method by which they are measured [2]. In natural or artificial multiphase materials, residual stress can arise from differences in thermal expansion or yield stress or stiffness. Nitriding is a chemically generated misfit, which produces a compressive residual stress in the near surface layers. Quenching and welding are examples for thermally generated misfits. Shot peening and grinding causing large compressive surface stresses, which fall of rapidly with increasing depth in to the body, are examples for cases where misfits are caused by non-uniform plastic deformation.

Aluminum with its unique characteristics of light weight, high strength, high toughness, extreme temperature capability and weldability make it an obvious choice of material by engineers and designers for a variety aerospace applications. Among the casting and wrought alloys of Aluminium, wrought alloys which can be shaped by rolling, drawing, forging etc are mostly used in aerospace applications. Among these wrought alloys, there are two major divisions namely heat treatable alloys and non-heat treatable alloys. In the case of heat treatable alloys, tensile strength which is important for aerospace applications, can be improved by heat treatment or cold working or by both. Commonly they are used in the T4 or T6 condition (solution heat-treated and naturally aged or solution heat-treated and artificially aged) whereas in T87 it is most stable. Base materials in these heat-treated tempers are in their optimum mechanical condition. The heat introduced to these base materials, during the welding process, can change their mechanical properties considerably within the weldment area. The effect from the heating during the welding on the heat-treatable alloy is generally a partial anneal and an over-aging effect. AA2219 is such an alloy, which has copper as the principal alloying element and find many applications where there is demand for high strength to weight ratios. This alloy has limited weldability and requires solution heat treatment to obtain optimum properties. Precipitation heat treatment is employed to further increase mechanical properties.

Gas-Tungsten arc welding (TIG) with Argon as shielding gas and filler metal of AA2319 material is normally employed for aluminium welding. Aluminum welding is different from that of other metals due to (a) the presence of Aluminium oxide on the surface which has a melting point of almost three times that of pure aluminium which is a cause for porosity, (b) its high thermal conductivity which demands higher heat input, (c) high thermal expansion coefficient which produces significant volume change in solidifying and causes distortion and cracking and (d) its low melting point. Weld defects typically seen are porosity, lack of fusion and cracks. In case of circumferential weld common in aerospace components, the weld overlap is difficult to be avoided. In these overlap regions, defects are increasingly seen and repairs need to be attempted, as the components are huge and costly.

Apart from the change in mechanical properties during welding, residual stresses also gets introduced. During welding, the weldment is locally heated and the temperature distribution is not uniform. As the molten metal solidifies, the areas farther away from the weld metal restrain the contraction of the weld metal and the adjacent base metal. Consequently, after cooling to the room temperature, residual tensile stresses exist in the weld metal and the adjacent base metal while residual compressive stresses exist in the areas farther away from the weld metal. Similarly, a different pattern of residual stresses gets induced along the transverse direction also. The original residual stress pattern also gets modified due to the thermal effects of the subsequent repair welds. The loss of strength in HAZ can be significantly affected by the welding process and by the heat input and welding speed [3]. However, even with the best-designed welding procedures, considerable loss in tensile strength is always experienced within the heat-affected zone when arc welding these types of materials. Unfortunately, it is usually either cost restrictive or, more often, impractical to perform post weld solution heat treatment because of the high temperatures required and the distortion associated with the process [4]. In this paper, the residual stress field in the HAZ of weld and the subsequent repairs are determined and an assessment is made on the integrity of the joint on its basis. The mechanical properties obtained from tensile testing of weld samples are also compared.

Methods of measurement

The different methods for residual stress fall broadly under Mechanical stress measurement methods, stress measurement by diffraction and other methods like Magnetic and Electrical techniques, Ultrasonic, Thermoelastic methods and Photoelastic methods [5]. Mechanical stress measurement methods rely on the monitoring of changes in component distortion, either during the generation of the residual stresses or afterwards, by deliberately removing material to allow the stresses to redistribute. Sectioning is a simple but destructive method of measurement. Hole drilling technique is another mechanical method, which can be considered to be semi-destructive.

The measurement of changes in inter planar spacing with reference to a stress free sample is made use of in methods using Diffraction of X-rays, Electrons, Neutrons and Synchrotron (or hard) X-rays of which X-ray diffraction method is the most commonly used. X-ray diffraction measures stress over a few tens of microns and is sensitive to grain size and texturing. The assumption of a plane stress condition over the sampling depth introduces errors in cases other than macro stresses which vary over large distances only.

Incremental Hole Drilling Method

The basic hole drilling procedure involves drilling a small hole of diameter 2 mm in to the surface of a component around which the relieved strain is measured using a rosette of strain gauges or other optical methods. From the measured strains, the residual stresses are computed using different methods. A variety of laboratory-based and portable equipments are available and the technique can be applied to a wide range of materials. The technique is semi-destructive as the volume of material removal is minimal which can be subsequently left alone or repaired. The hole drilling principle was first proposed by Mathar in 1934 [6] and since then further developed in to a standardized procedure ASTM E837 [7]. The standard refers to evaluation of in-plane residual stresses of magnitude less than half of the yield stress that can be assumed to be uniform with depth either from the surface of a thick specimen or through the thickness of a thin specimen.

In most practical cases, the residual stresses are not uniform with depth. The Incremental hole drilling method is an improvement on the basic hole drilling method, which involves carrying out the drilling in a series of small steps, which improves the versatility of the method and enables stress profiles and gradients to be measured. A high-speed pneumatic drill, which runs above 3 lakhs rpm, is used to drill the hole. The very high rpm drilling has been found to introduce no further machining stresses and thereby no modification to the existing stress system. The strain data at pre-determined depths are precisely acquired.

Different stress calculation methods are used to arrive at the residual stress system from the measured strains. The major techniques in vogue are Uniform Stress, Equivalent Uniform Stress, Power Series and Integral methods [8]. Uniform stress method is specified in ASTM E837. Power series method is an approximate method of calculating non-uniform stress fields from incremental strain data. It assumes a linear variation of residual stress with depth. In the Integral method, the contributions of the total measured strain relaxations of the stresses at all depths are considered simultaneously [9]. This provides a separate evaluation of residual stress within each increment of depth. Thus, the method has the

Table 1 Specimen used for the study with measured mechanical properties

Sl No.	Identification No.	Details of weld	Average mechanical properties obtained from tensile sample testing		
			0.2% YS MPa	UTS MPa	% Elongation
1	Specimen A	First weld (auto)	149	252	5.3
2	Specimen B	First Repair pass (auto) R1	155	278	4.9
3	Specimen C	Second Repair pass (auto) R2	162	265	4.5
4	Specimen D	Third Repair pass (auto) R3	149	269	4.7
5	Specimen E	Manual weld	150	275	5.4
6	Parent Metal (T6)	-	304	417	10

highest spatial resolution and is useful for measuring rapidly varying residual stresses. The method gives a good stepped approximation to the actual stress variation with depth. In any case, a meticulous measurement practice is crucial to obtaining good quality strain data and the application of the correct analysis method to the relieved strain data can provide accurate assessment of the residual stress system present [10].

Measurement in the HAZ on Aluminium weldments

As a part of the welding technology development of AA2219 material, Automatic AC TIG Welded plates originally in T6 condition with various weld conditions like First weld and subsequent repair passes and a similar specimen with manual weld have been generated for studies. The specimen details are given in Table 1. The mechanical properties obtained from tensile testing of weld coupons are also included.

Plates have a minimum dimension of 210 mm 125 mm with weld in the center. Measurements were made on a location near to the weld as well as away from the weld for the specimen of first weld (automatic). Subsequently, for the other specimens, only near weld measurement has been made. All the subsequent repair passes have also been made of automatic welding. Hole was drilled up to 2.0 mm depth in the plate in the center of the strain rosette make HBM 1.5/120 RY 61K as per the standard procedure and the strain data was acquired. The residual stress was computed to 0.8 mm depth using the Integral method. The principal stress data has been compared to see the modifications occurring in the stress system with additional passes. The manual weld also has been compared with first weld (auto). Two measurement trials were made near weld for the First weld (auto) specimen. The results were quite similar in magnitude but slightly different in orientation. In the same way measurement for the third repair specimen also was repeated and results found to be similar.

Results and discussion

The maximum principal stresses measured in the automatic and manual welds till a depth of 0.8 mm is compared with the original stress system as measured in a loaction away from the weld in Fig.1. The residual stress measured in the HAZ of the weld with the hole drilled 2.5 mm from the weld toe for the automatic and manual weld specimen shows quite a difference. The automatic weld introduces a maximum stress of around 100 MPa for quite a depth where as the stress varies linearly to around 60 MPa only in the case of manual weld. The specimen initially being in the T6 condition is expected to have a small compressive stress inside and the same is observed on measurement. The weld speed for manual speed is almost half of the speed for automatic welding. The higher speed of the automatic welding introduces higher thermal gradients in the specimen. This results in a higher residual stress field. Manual welding of large components is not practical as restarts introduce overlaps and increasing defects. The UTS of the automatic weld specimen reduces to 252 MPa and it is 275 MPa for manual weld where as 417 MPa is obtained for parent metal samples. The reduction in UTS for weld specimen also matches the trend of the magnitude of the residual stress measured.

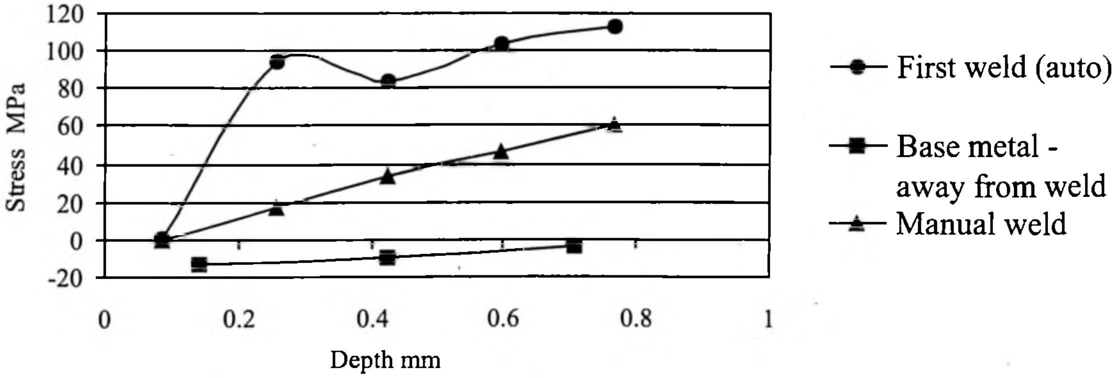

Fig.1 Comparison of maximum principal stress with automatic and manual welds

It is seen from the graph plotted in Fig.2 that the residual stress system gets considerably modified with subsequent passes. The average principal stress value is brought below 40 MPa with first and second repair passes. This is expected because of the annealing effect of the subsequent passes. There is not much difference in the magnitude of maximum principal stress between first and second repair passes though a difference is seen in the orientation. Comparing the minimum principal stresses between these passes, the stress value for the second pass is seen to have been modified to result in a nominal compressive stress as shown in the Fig. 3 by the addition of compressive stresses during the second repair pass. The minimum principal direction is at an angle of 63 degree to the line of weld direction in case of second repair where as it almost 33 degree for first repair. The maximum principal stress value in case of third repair is seen to increase again to approx 55 MPa. The UTS measured for the first repair pass specimens is seen to have improved almost 10% from the value obtained for first weld specimen. The corresponding values for second repair and third repair specimen are only 6.7% and 5% respectively. This trend broadly matches with the trend seen in residual stresses measurement. The percentage of elongation for all welds is reduced indicating low ductility.

Approximate bulk residual stress values estimated at a depth of beyond 1mm using Power series method is given in Table 2. The trend is similar as in the case of integral method of analysis except a higher value is obtained for third repair. This method assumes that the stress field varies linearly only and hence some local peaks are missed in this analysis. This simplifying assumption introduce errors in the calculated values of residual stress compared to that obtained using integral method.

Conclusion

From the stress field plotted against depth, it can be seen that stress field at times changes from a compressive field to a tensile field at a very shallow depth and that too beyond a depth of 0.1 mm, which cannot be detected by surface methods of measurement like X-ray diffraction. Also, only an aggregate stress value near surface can be obtained, though sharp gradients are normally

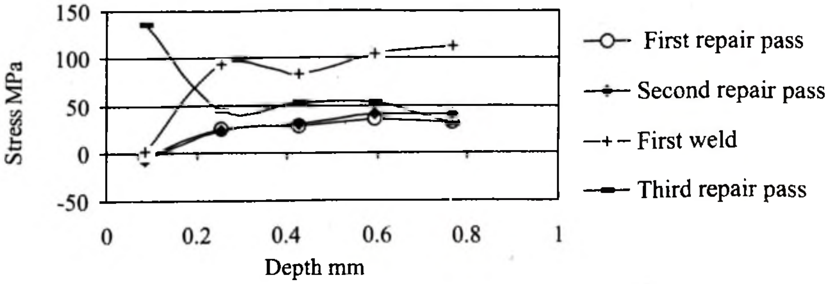

Fig.2 Comparison of maximum principal stress for specimen with repair passes.

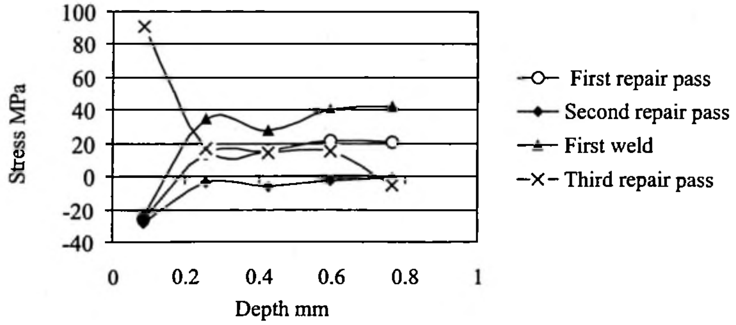

Fig.3 Comparison of minimum principal stress for specimen with repair passes.

Table 2 Approximate bulk stresses calculated from Power series method

Sl No.	Identification No.	Details of weld	Average bulk principal residual stress values obtained		
			Maximum MPa	Minimum MPa	Orientation of max stress with weld line in degrees
1	Specimen A	First weld (auto)	71	10	39
2	Specimen B	First Repair pass R1	20	7	57
3	Specimen C	Second Repair pass R2	25	-16	26
4	Specimen D	Third Repair pass R3	70	33	28
5	Specimen E	Manual weld	28	2	17
6	Parent Metal	-	-10	-15	0

present. It is seen that the effect of welding process could be assessed through the measurement of non-uniform residual stress field up to a depth of 2 mm through the incremental hole drilling process. This technique can provide sufficient information to the designers and fabrication engineers to decide on the fabrication process of components with the optimum methods and heat treatments during production trials itself.

With repeated passes of welding, the quality of weldment is brought down by the increased presence of defects. The study carried out has brought out the sharp increase of residual stresses with the third repair pass compared to the first and second passes. This proves that a maximum of two weld repairs are permissible from the point of view of the magnitude of the residual stresses introduced in the HAZ. The welding standard followed in the institution, derived after years of experience in the fabrication process, permits only up to two repairs of weld. This has been confirmed to be reasonable from the residual stress measurements carried out. The weld coupon testing has brought out a reduction in strength between the parent metal and the welds, but does not provide information on the effect of repeated weld passes conclusively.

References

1. T. Mura, "Micro-mechanics of defects in solids", Martinus Nickoff, Publishers, The Netherlands, 1982
2. P. J. Withers and H. K. D. H. Bhadeshia, Material Science and Technology, 17, 2001, 355-365
3. Sindo Kou, "Welding Metallurgy", Second Edition, Wiley-Interscience
4. Tony Anderson, AlcoTec Wire corporation, MI, USA, "The Repair of Aluminium Structures" E Mail: tanderson@alcotec.com
5. P. J. Withers and H. K. D. H. Bhadeshia, Material Science and Technology, 17, 2001, 366-375
6. J. Mathar, Trans. ASME, 56 (4) 1934, 249-254
7. ASTM E 837-01, Standard test method for Determining residual stresses by the Hole Drilling Strain-Gauge Method, 2001
8. P. V. Grant and J. D. Lord, "A Evaluation of four Hole Drilling Analysis techniques with respect to Non-uniform Residual Stress Fields", MATC(MN)31, National Physical Laboratory, UK, August 2002.
9. G. S. Schajer, J. Eng. Materials and Technology, 110 (4), 1988, Part-I: pp 338-343, Part II: pp 344 -349
10. P V Grant, J D Lord and P S Whitehead "The measurement of residual stresses by the incremental hole drilling technique" Good Practice Guide No. 53, National Physical Laboratory, UK