FINITE ELEMENT ANALYSIS AND EXPERIMENTAL VALIDATION OF RESIDUAL STRESS ANALYSIS IN T-WELDED ZONE OF ALUMINUM ALLOY 6061-T6

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ABSTRACT

Residual stresses induced during welding process are neglected in most of the engineering applications; however, the significance of residual stresses cannot be neglected in applications of significant concern such as defense vehicles, pressure vessels etc., as these leads to stress concentration, corrosion, cracking, distortion, fatigue cracking, premature failures in components and instances of over-safe design. This paper illustrates importance of residual stresses characterization in Aluminum alloy plate welding. This work focuses on the behavior of residual stress for Aluminum Alloy structure in 6061-T6 with a filler weld material ER5356 and further to improve the weld life of such joints. Experimentation for each weld parameter has been carried out and this gives a better understanding of the weld behavior for stress concentration. For this work, major focus is on feeding travel rate and the results are evaluated numerically by means of finite element method. The FE analysis allows highlighting and evaluating the stress factors and its gradients by means of heat affected zones (HAZ). The experimental validation of residual stress measurement through X-ray diffraction technique (XRD) carried out at Automotive Research Association of India. Comparison of the experimental and analytical results reflects a comprehensive solution for the optimized value of residual stresses, strains and distortion in welded structure.

KEYWORDS: Aluminium Alloy, T-Welded Joints, Heat Affected Zones, X-Ray Diffraction & Finite Element Analysis

Received: Jul 04, 2018; **Accepted:** Jul 25, 2018; **Published:** Aug 23, 2018; **Paper Id:** IJMPERDAUG2018120

INTRODUCTION

Now-a-days, most of the automobile, agricultural, off-shore equipment manufacturing industries invests in design changeover from Steel structures to Aluminum structures due the multiple gain factors such as weight reduction, cost reduction and manufacturing feasibility. As there are always some cons associated with the pros that the design engineer need to consider and evaluate the root causes behind them. Fatigue failure is still a dominating cause for breakdown of welded structures, hence leading and contributing to substantial cost.

In present work, major focus is on automobile and agricultural equipment manufacturing aspects. The demand of a sustainable automobile product needs attributes such as structures with lower weight, better performance in terms of durability and reduced fuel consumption. This leads the use of efficient and accurate fatigue design methods adhering to quality requirements of the product during design phase itself. Survey reflects

that eighty per cent of the main structure and components in machinery are welded. Aluminum structures are fabricated from a variety of different aluminum grades. Welding these materials gives a rise to local stress concentration and residual stresses.

T-WELD MATERIAL PROPERTIES AND PARAMETERS

Presently a wide variety of Aluminum Alloys is available which can be used as per required load/applications. In present research work research consideration is adhered to 6061-T6 alloy which is hard strength material to carry a load and commonly used in Automobile and Agricultural equipment manufacturers. ER 5356 is also suitable as filler material for better weld bonding.

ELECTRICAL PARAMETERS

Two welding passes were carried out separately with opposite welding directions. The initial welding parameters were wavelength of 1.06 μm , focus diameter of 0.6 mm, focus position at 8 mm from flange, laser-arc distance (i. e. distance between the laser beam and tungsten electrode) of 1 mm, laser-arc angle of 25°, wire diameter of 1.2 mm, wire extension dimension of 12 mm, peak current of 142 amperes, background current of 26 ampere, average voltage of 20 Volts and the wire feed rate of 6.6 mm/second.

The residual stresses vary with reference to variable electric parameters (as voltage and current) and are out of control of the user. The parameter of wire feed rate is prominently under the control of the operator and varies according to usage or operator experience. Hence variable feed rates are considered in the present study. The feed rate was varied 3 times as 6.6 mm/sec, 5mm/sec and 4mm/sec and results were accounted for further consideration of research.

Table 1: Parameters used in Experimentation

Nominal Plate Thickness, mm	Filler Wire Diameter mm	Pick Current, A	Volts, V	Wire Speed, m/min	Travel Speed mm/sec
3	1.2	140	19-21	14-15	6.6
					5
					4

COMPUTER AIDED MODELING AND SIMULATION OF THE T-WELDED JOINT

To understand the weld behavior during welding process as well as when subjected to loading situation, computer aided modeling and simulation (i. e. finite element analysis) of the welded joint is carried out. The computer aided model of the test specimen is prepared using CATIA software. Overall dimensions of the weld assembly are 120x120 mm. The dimensions of flange portion are 120x120x3 mm and that of web portion are 120x50x3 mm. Three-dimensional model of the whole T-joint assembly is prepared. All the actual dimensions are assigned to the computer model. The thickness assigned to the flange and web is 3 mm. The entire model along with the welded portion of the T-joint is shown in figure1.

Figure 1: Computer Aided Model along with Dimensional Details of the T-Joint

MESHING OF THE COMPUTER AIDED MODEL

To simulate the weld behavior at every location on the T-joint, it is discretized into small elements. Considering the thickness, length, height and width of web, weld and flange in the T-joint, eight node hexahedral elements were used for meshing of the whole assembly. Meshing is carried at the mid-surfaces of the whole joint. Material properties assigned to the base Aluminum alloy 6061-T6 density of 2700 kg/m³, thermal expansion coefficient of 23.4×10^{-6} /K, thermal conductivity of 166W/m. K, elastic modulus value of 67500 MPa, Poisson's ratio of 0.34 and that of filler material ER5356 are Poisson's ratio of 0.33, yield strength of 110 MPa, density of 2657 kg/m³, elastic modulus of 70000MPa and thermal conductivity of 221W/m. K. Manual meshing has been carried out in present work, reason being large temperature drop (or difference) from weld to its surrounding and then further in the remaining portions of the web and flange i. e. from heat affected zones to the end of flange. Node to node coincidence and element connectivity is verified to ensure accurate results. The finite element model was established on 1:1 scale. Finer mesh size or grids are used at the weld and its surrounding areas on both flange and web and coarse mesh size or grids are adopted in the remaining portions of the T-joint. The finite element model geometry is divided into 37280 eight-node hexahedral elements and 202770 nodes. The meshed model of the structure is shown below figure 2.

Figure 2: Meshed Model of the T-Joint Welded Structure

The Boundary conditions for transient thermal analysis are applied at the nodes of base alloy and filler alloy interfaces. Boundary conditions are the temperature values obtained during the real-time in a time span of 0 to 36 seconds. Transient thermal analysis of the weld has been carried out to evaluate the variation of temperature during weld process. In transient thermal analysis, the applied loads are functions of time. The temperature variation during welding and subsequent cooling is evaluated by heat conduction and natural convection method. The temperature values are then tabulated in table 2 and in further step this temperature field is applied to the meshed model at respective 48 weld throats to evaluate residual stress in the weld. Simulation of welding rod speed with 6.6mm/second has been performed and the same

is repeated for weld rod speeds of 5mm/second and 4mm/second respectively. By varying the weld-rod travel speed rate over the entire length of weld, evaluation of the thermal and residual stresses (Principle stresses) has been carried and the finite element analysis results are compared. Further to evaluate the deflection and stress static structural analysis has been carried out.

Table 2: Weld Temp Input Values

Time (sec)	Temperature (°C)							
	1	2	3	4	5	6	7	8
0	27	27	27	27	27	27	27	27
0.75	550	500	470	450	440	430	420	410
1.5	500	550	510	470	450	440	430	420
2.25	480	510	550	510	470	450	440	430
3	400	490	520	550	520	470	450	440
3.75	350	400	490	520	550	520	470	450
4.5	300	350	410	480	510	550	520	470
5.25	260	300	360	400	480	520	550	520
6	200	260	300	350	400	470	520	550

The boundary conditions for structural analysis are defined to have a frictionless support at the bottom surface of the flange plate and added the self-weight to the material are shown in figure 3.

Figure 3: Boundary Conditions: Frictionless Support

TRANSIENT THERMAL ANALYSIS

During the transient thermal analysis, actual temperature variations are achieved with respect to weld rod feed rate and this phenomenon are simulate in the Transient thermal analysis. After this phenomenon, the weld specimen is cooled by nature convection with respect to time 6000sec to reach the ambient temperature 27°C. The results obtained from the transient thermal analysis are shown in table 3 and figure 4,

Table 3: FEA Results of Residual Stress and Shear Stress

Sr. No	Location on Flange	Residual Normal stress(σ) in MPa	Nature of Stress	Residual Shear Stress(τ) in MPa	Nature of stress
01	Location 1	-350 $\pm$ 20	Compressive	0.16 $\pm$ 1.2	Shear
02	Location 2	-54 $\pm$ 10	Compressive	-7.2 $\pm$ 1.1	Shear
03	Location 3	-20 $\pm$ 10	Compressive	8.9 $\pm$ 1.1	Shear

Figure 4: Principle and Shear Stresses

STATIC STRUCTURAL ANALYSIS

Static structural analysis is carried out to measure the temperature behavior and deformation during welding. Results obtained from the structural analysis are as per Figure 5,

Figure 5: Temperature Distribution around the Weld Throats and Deformation Behaviour

EXPERIMENTATION OF THE T-JOINT WELD SPECIMEN

Experimentation of the T-joint weld specimen this research work has been carried for Aluminum structure welds for evaluation of fatigue strength and other allied factors. To have a thorough understanding of the behavior of the welded structure a test specimen of T-joint has been prepared for testing. The base material and the filler materials used for this work are 6061-T6 aluminum alloy and ER5356 aluminum alloy welding wire. The fillet welding was conducted on the aluminum alloy T-specimens, as shown in figure (Figure No 5). The flange and web dimensions are 120 x 100 x 3 (mm) and 120 x 50 x 3 (mm) respectively. During the laser welding process, laser was in front of arc and welding torch was tilted at an angle of 30° with respect to the flange of T-section is carried out to analyze the residual stresses induced due to welding process. The residual stresses are measured by X-ray diffraction technique. This experimentation is carried out at Automotive Research Association of India. Three different locations were selected on the flange. Heat affected zones were identified as three different locations. Location 1 is selected in the area near the welded zone, location 2 is selected at the mid of the flange and location 3 is selected near the outer edge of flange, the joint being symmetric the locations are selected only on one side. The 3 locations along with the direction of scan and experimental setup for experimentation is shown in figure 6.

Figure 6: Locations for Measurement of Residual Stress and Direction of Scan and Experimentation Setup

The specifications of the instrumentation used are as mentioned as: X-Ray diffract meter Make: P-Analytical, X'PERT PRO, $K\alpha$ radiation: Cobalt source, Wavelength: $1.789010 \mu\text{m}$, Parallel beam geometry with poly-caliper lens and parallel plate collimator, X-Ray elastic constant $18.73 \times 10^{-6} \text{ MPa}$, Bragg angle: 148.520

Experimental observations are tabulated in table 4 below. Both compressive and shear residual stresses are observed in the heat affected zones. As postulated from finite element analysis the magnitude of compressive residual stress goes on decreasing from location 1 to location 3. Compressive residual stress is predominant over residual stress and the magnitudes of same are given in table 4.

Table 4: Test Results for Normal Residual Stress and Shear Residual Stress

Sr. No	Location on Flange	Residual Normal stress(σ) in MPa	Nature of Stress	Residual Shear Stress(τ) in MPa	Nature of stress
01	Location 1	-308 ± 20	Compressive	1.2 ± 1.2	Shear
02	Location 2	-50 ± 16	Compressive	-8.6 ± 1.1	Shear
03	Location 3	-16 ± 16	Compressive	7.0 ± 1.1	Shear

Figure 7: Graph Location Points 1, 2 and 3

CONCLUSIONS

As the applications of aluminum alloy 6061 include a wide range including rail coaches, truck frames, military bridges, helicopter rotor skins, boilers, motorboats and rivets, analysis of residual stresses is of significant concern. From the experimental and finite element analysis results, following are the inferences drawn:

- Residual stress is of significant concern in case if the failure leads to substantial financial loss or danger to human life.
- Temperature variation in the proximity of weld areas in the time span of 0 to 36 seconds reaches a maximum value of 550 degree centigrade.

- From experimental analysis, it is observed that compressive stresses share a dominant magnitude of residual stresses. The maximum value of compressive stress is observed near the weld proximity at location 1 and the magnitude is 308 MPa whereas the least value of residual compressive stress is observed at location 3 and the magnitude of same is 16MPa
- Experimental analysis also reveals that residual shear stresses are induced into the base alloy material. The magnitude observed at location 1 and 3 are 1.2 and 7.0 respectively. However residual shear stresses are of least significance.
- Graphs of $\sin^2(\Phi)$ vs d-spacing are also constructed from experimental analysis results. Graph 1 shows linear behavior between $\sin^2(\Phi)$ vs d-spacing, whereas other graphs shows parabolic behavior.
- On graph 1, the value of $\sin^2(\Phi)$ is zero for d-spacing values between 0.92930 and 0.92925 and similarly on other graph, the value of $\sin^2(\Phi)$ is zero for d-spacing values between 0.9292 and 0.9293.

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