# Analysis of Internal Stresses in Alumina-Mild Steel Welded Tubes Using Finite Element Method

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## ABSTRACT:

This study presents a finite element analysis (FEA) of internal stresses in welded tubes composed of alumina and mild steel, aiming to understand the mechanical behavior of these hybrid materials under various loading conditions. The welding process introduces complex stress distributions that can significantly affect the structural integrity and performance of welded joints. This research employs advanced FEA techniques to model the geometry and material properties of the alumina-mild steel tubes, allowing for a detailed examination of the internal stress profiles resulting from welding. The analysis focuses on identifying critical stress concentrations, evaluating the effects of temperature variations during welding, and assessing the overall structural response of the welded assembly. Results indicate that the interaction between the dissimilar materials leads to unique stress distributions, with implications for joint durability and failure mechanisms. This study provides valuable insights for engineers and designers in optimizing the welding process and enhancing the performance of alumina-mild steel hybrid structures in various industrial applications. The findings contribute to the growing body of knowledge on the behavior of welded composite materials, paving the way for improved design methodologies and material selections in engineering practice.

**Keywords:** friction welding, intermetallic, FE model, interface, bending strength
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## 1.0 **INTRODUCTION**

Welding dissimilar materials, such as alumina and mild steel, is increasingly common in various industrial applications due to the unique properties these materials offer. Alumina, known for its excellent wear resistance, high thermal stability, and low density, complements mild steel, which provides superior ductility and tensile strength. However, the welding of these two materials presents significant challenges, particularly concerning the management of internal stresses that arise during the welding process. These stresses can lead to distortion, reduced structural integrity, and premature failure of welded joints, making it essential to understand their behavior in hybrid assemblies.

The welding process itself introduces complex thermal gradients and phase transformations, which contribute to the development of residual stresses. These stresses can vary significantly across the welded joint due to differences in thermal expansion coefficients, mechanical properties, and the physical characteristics of the materials involved. Consequently, analyzing the internal stress distribution in welded alumina-mild steel tubes is critical for predicting the performance and longevity of such structures.

Finite element analysis (FEA) has emerged as a powerful tool for investigating stress distributions and evaluating the mechanical behavior of welded components. By creating detailed computational models that simulate the welding process, FEA allows for the exploration of various factors, including temperature gradients, welding techniques, and material properties. This study aims to employ FEA to analyze the internal stresses in welded alumina-mild steel tubes, providing insights into the effects of welding on joint integrity and performance.

The objectives of this research include identifying critical stress concentrations, understanding the implications of welding-induced stresses, and proposing strategies to mitigate potential failures. The findings will not only contribute to the understanding of the behavior of hybrid materials in welded assemblies but also aid in the optimization of welding processes for improved performance in applications ranging from automotive to aerospace engineering. By enhancing the knowledge base in this field, this study aims to support engineers and manufacturers in developing more reliable and efficient welded structures that leverage the advantages of both alumina and mild steel..

## 2.0 LITERATURE REVIEW

In recent years, the use of joints between dissimilar metals has considerably increased. In the development of new technologies for the aerospace, medical and automotive industries, these junctures are of high importance, because they allow the systems, components manufactured in mild steel and aluminum to be structurally united Sepe, R.; Armentani**[5]** performed a study in a dissimilar welding butt joint (titanium and aluminum), using a fiber laser welding method. 2D and 3D Gaussian heat source were used to study the thermal analysis of this welding process. The experimental fusion zone of the joint was compared with the numerical one. During the welding cycle, the actual temperature was registered and was validated by the numerical model. To calculate fusion zone’s dimension, the 2D model demonstrated better accuracy than the 3D. Dhinakaran, V.; Siva**[6]** developed a simulation model considering both in-plane and out-of-plane distortions. This model was validated with case study analysis and the results demonstrated good agreement in predicting and diagnosing the in-plane variation.Dhinakaran et al**[7]** performed a finite element analysis to understand multi-layer rotating arc narrow gap MAG welding for medium steel plate. Temperature field was solved and analyzed in multi- layer rotating arc welding based on element birth and death technique. The simulation results were in good agreement with the experimental data, 1.5 mm of difference between them. Residual stress and deformations were calculated based on temperature fields in four welding conditionsDerakshshan et al**[8]** performed full 3D simulations in studying the start/stop in partial repair effects. The start and stop events have been simulated in 3D, and comparison, with 2D results, indicate a significant increase in weld residual stresses. These events are harmful to reliability since the extra thermal and mechanical loading increases the stress height, which can influence the crack depth or the initiation of failure by Balran, Y.; Babu **[9]** Finite element model has been developed to predict the temperature fields and residual stress distribution in weldments. A coupled sequentially thermo-mechanical transient analysis was used to carry out with ANSYS 16.0. The temperature dependent properties of base metals are considered during the welding modeling. The heat flow rate during the welding due to conduction, convection and radiation was considered Balakrishnan, J **[10]** In this work we assess the effects that two current technologies, and two candidate technologies for future build programmes, are likely to have on the generation of residual stresses within critical nuclear components. Single-sided welds were manufactured in 30 mm thick plates of SA508 steel, using four welding processes: gas-tungsten arc welding (GTAW), submerged-arc welding (SAW), multi pass NGLW and RPEB welding.

## 3.0 METHODOLOGY

In the experimental study, rods 10 mm in diameter made of alumina (50 mm length) and mild steel (50 mm length), and Al6061 sheet (0.3 mm, 0.5 mm, 1.0 mm and 1.5 mm) interlayers were used. The connection surfaces of mild steel and alumina were ground to smooth and sharp edges around it. The experimental setup for the FW process is shown in

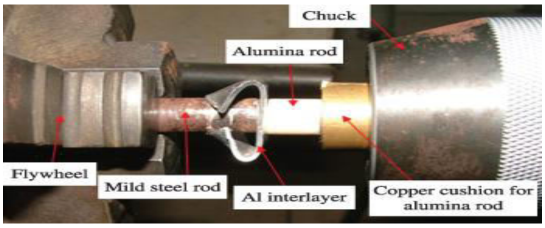

**Figure 3.1: Experimental setup**

The friction welded sample was sectioned perpendicular to the weld interface and polished. Macrograph and microstructure of the weld interface were obtained using Dino-Lite digital microscope and Field Emission Scanning Electron Microscopy (FESEM) (model VPFESEM SUPRA 35VP) machine respectively. Electron-probe microanalysis (EPMA) was carried out across intermediate layers to determine the variation of element concentration using FESEM. The successfully welded samples at various friction times were also measured for their four-point bending strength using Instron machine (model 8501) and Knoop hardness test.

The friction welding process was done on a continuous drive friction welding machine. The friction welding conditions were 900 rpm rotational speed and 20 MPa axial pressure. The bending strengths and hardness values of the welded samples were determined. The successful joined alumina-mild steel rods are shown

**Figure 3.2: Alumina and steel weld joints**

The main heat source in FW is generally considered to be the friction between the rotating rod (mild steel)-interlayer (aluminium alloy) sheet surfaces and the un rotating rod (alumina)-interlayer (aluminum alloy) sheet surfaces, and the "cold work" in the plastic deformation of the interlayer. The heat generation from the plastic deformation of the aluminum is considered to some extent in the model with the use of variable friction coefficient and not explicitly accounted for as a heat source. The heat is generated at the interface of the rotating steel rod and the aluminum sheet due to friction and plastic deformation

### Boundary and initial conditions

The conduction and convection coefficients on various surfaces play an important role in the determination of the thermal history of the workpiece in friction welding. The initial and boundary conditions considered in this model are based on the actual conditions exhibited in experiment figure shows the various boundary conditions applied on the model.

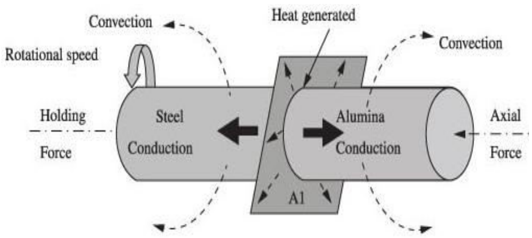

**Figure 3.3: Boundary conditions applied weld joints**

### FEM model

To model the actual physics phenomena of the FW process is rather complicated. Therefore, several simplifying assumptions have been made. The assumptions made when defining the loads and boundary conditions for the simulation are

Perfect elastic-plastic behaviour of the work pieces material was assumed also to reduce computer time requirements;

- The interlayer and rods were assumed to experience frictional contact described by Coulomb's frictional law with temperature dependent friction coefficient, μ;
- The friction coefficient, μ below material melting point were assumed to be zero following the tendency from the experimental chart[13];
- The radiation heat loss was neglected as it was considerably less compared

to the conduction and convection losses.

The alumina and steel rods were modelled in the computational domain of 20 mm length and 10 mm diameter each. The aluminum alloy sheet was modeled in the computational domain of 1.42 mm thickness and 12 mm diameter. The alumina and steel rods were modelled using 3D solid (continuum) elements as deformable rigid constrained. The aluminum sheet was modelled as a solid and deformable element. The attachment of aluminum sheet to the steel rod end surfaces was considered to be perfectly.

In this analysis, a uniform connection was assumed. The plasticized zone was the heat generated and affected area where the aluminum turned to be softened due to severe friction. In this zone the material model of Johnson-Cook and adaptive meshing were incorporated during simulation to enable the occurrence of the aluminum deformation. Coulomb friction law has been selected for the modelling of the workpieces interface contact. Heat transfer is allowed on the components contact area. The boundary conditions, contact conductance in the heat sink, the convection on the external surfaces and sliding surfaces on contact surfaces are applied on the assembled components of aluminum, steel and alumina. Initial temperatures for all components were assumed at 29 °C. The aluminum alloy edge was constrained to move axially.

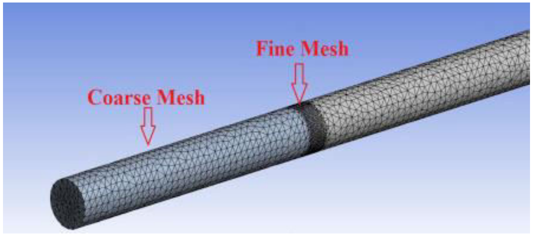

**Figure 3.4: Fem model friction weld process**

The FE analysis was conducted by prescribing steel rod rotation and followed by displacement of the alumina rod with appropriate boundary conditions. The friction welding simulation was prescribed in three-time steps, based on an actual experimental setup. In the first step, the steel rod was rotated at angular velocity of 94.3 rad/s. Then in the second step, the alumina rod was axially displaced with a rate of 20.8 m/s to the aluminum alloy sheet. Lastly in the third step, after the rubbed interface reached appropriate welding temperature, the rotating steel rod was stopped for cooling stage.

## 4.0 RESULTS AND DISCUSSION

The reliability of friction-welded ceramic-metal joint with the use of interlayer depends upon the bending strength of the joint which is usually related to interlayer thickness and friction time of the joint. In this section, the relationships between the interlayer thickness, friction time and bending strength were investigated. Here, the bending strength was the average value of 4 joints welded under the same welding conditions. Most of the tested samples fractured in the alumina rod part indicating that the joint is stronger than the brittle alumina body. Most of the tested samples fractured in the alumina rod part as shown in figure This indicates that the joint is stronger than the brittle alumina body.

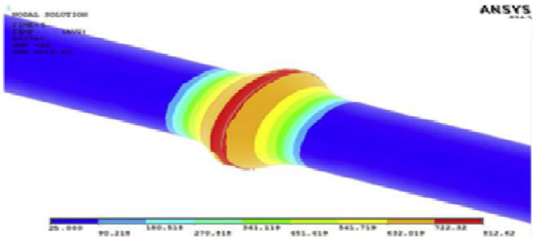

**Figure 4.1: Simulated thermal distribution-1**

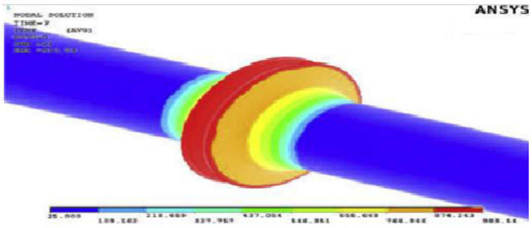

**Figure 4.2:Simulated thermal distribution-2**

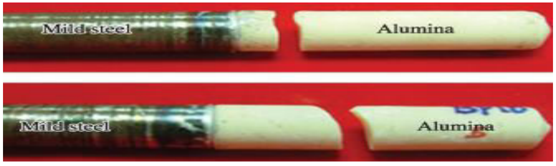

**Figure 4.3; After bending test samples**

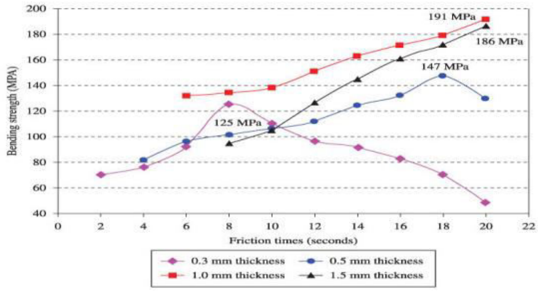

**Figure 4.4: Inter layer thickness friction time bending strength of the joints**

shows the above figure relationship between the interlayer thickness, friction time and bending strength of the joints. The use of interlayers1.0 mm and 1.5 mm in thickness revealed that the bending strength increased almost proportionally with the increase in friction time ranging from 60 to 200 MPa, except for joints with 0.3 mm and 0.5 mm interlayers.

## HARDNESS PROPERTY AT DIFFERENT POINT NEAR THE BONDLINE:

The hardness profile near the bondline of the alumina-mild steel joint is shown in figure the hardness profile in the alumina part exhibited insignificant change and remained constant like before the friction process occurs, i.e. within the range of 1300-1700 KHN. Because alumina has inert, hard and brittle properties, only aluminum atom diffusion occurs at the contact surface during the friction process. On the other hand, the hardness value for the mild steel part slightly increased towards the joint (reaching 200 KHN). This resulted from the effects of the formation of the narrow brittle intermetallic phase at the mild steel - aluminum interface, as discussed in the interfacial microstructure characterization

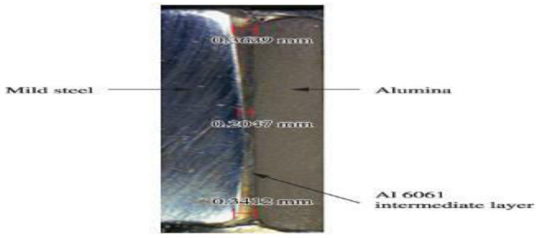

**Figure 4.5: Weld cross section**

## Temperature distribution

Since the heat flux is generated at the rod/interlayer interfaces, the heat flows through the intermediate layer into the alumina and steel rods creating a thermal profile. The simulation is stopped when the maximum aluminum temperature reached reasonable value below its melting point as discussed earlier in section It is observed that the heating temperature of the aluminum-alumina is in the range of 400-450 °C to obtain the joint as has been claimed in the past from other author the variation of the temperature in the cross-section of the joint and the rubbing surface of the interlayer throughout the simulation run for the constant steel rod rotation speed of 900 rpm. Increase rapidly in axial load increases the surface heat flux in the deformed aluminum, particularly in the region adjacent to the rods periphery. This leads to higher temperatures which are observed in the simulation results. As it can be observed a maximum temperature of 449.4 °C has been achieved in the early deformed aluminum sheet at 0.0001 seconds.

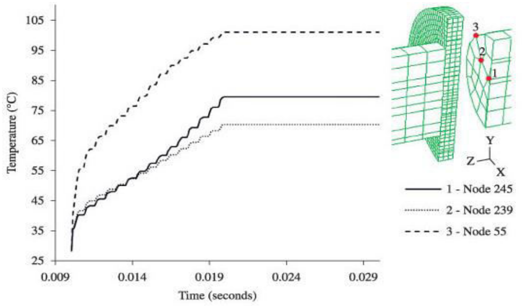

**Figure 4.6: Weld joints entire process period**

The temperature increases rapidly from room temperature up to almost 130 °C. Due to friction mechanism, the temperature then rises and fluctuates further until 150 °C before slowly decreases when the steel rod rotation is stopped. Following the same trend, both inner nodes 245 and 250 show overlap curves. During the FW process, temperature at the two nodes increase rapidly up to 110 °C and steadily rises up to 150 °C before slowly decreases after the FW stopped.

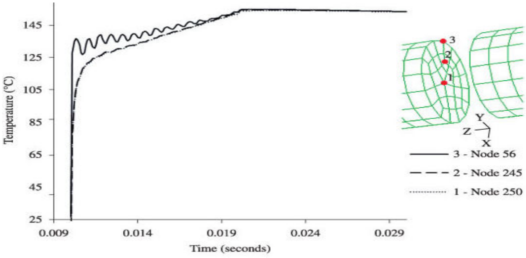

**Figure 4.7: Temperature at friction steel - Alumina function of time during period**

## STRAIN AND STRESS DISTRIBUTION

Figure shows the Von Mises stress and equivalent plastic strain contour maps of the interlayer rubbing surface at friction welding time of 0.0053 seconds. As it can be observed, the maximum plastic strain reaches the value of 6, and is generated where the largest plastic strains take place in the material close to the rod periphery, since the material is subjected to intense deformations due to the rod's translational and rotational motion. This issue matches with the maximum deformed interlayer temperature found at the same zone.

Regarding the Von Mises stress distribution shown in figure it is important to keep in mind that, in the model, the yield stress was given as a function of temperature and the values ranged from around 510 MPa at room temperature to less than 21 MPa at temperatures greater than 300 °C. As can be observed, the material close to the contacted rod experienced yielding and the maximum stress appears in the interlayer contacted surface, near the periphery zone of the contacted diameter.

There are several key parameters in the model that have a significant impact in the simulation results: the coefficient of friction between the rod and the interlayer material, the limiting shear stress that controls the stick/slip condition between contacting surfaces and the distribution of frictional heat between the rod and the interlayer sheet. Ideally, carefully designed experiments should be conducted to determine the value of those parameters.

## CONCLUSIONS

In conclusion, this study has successfully utilized finite element analysis (FEA) to investigate the internal stress distributions in welded tubes composed of alumina and mild steel. The results reveal that the welding process induces significant residual stresses due to the differences in thermal expansion and mechanical properties of the two materials. Notably, the analysis identified critical stress concentrations at the weld interface, which are essential for understanding potential failure mechanisms in hybrid structures. By highlighting the effects of welding parameters and material properties on internal stresses, this research provides valuable insights for optimizing the welding process to enhance joint integrity and performance. The findings emphasize the importance of considering material interactions in the design of welded assemblies, paving the way for improved methodologies in welding dissimilar materials. Future work could explore advanced welding techniques and post-weld treatments to further mitigate stress concentrations and improve the durability of alumina-mild steel hybrid structures. Overall, this study contributes to the growing body of knowledge on the behavior of welded composite materials, offering practical implications for engineers and manufacturers aiming to leverage the unique properties of both alumina and mild steel in various industrial applications.

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