Feasibility and Insights into the Optimization and Characterization of Friction Welded Aluminum–Steel Dissimilar Joints

S. Hari Krishna Raj, G. Boopathy, S. Vijayananth, G. Balaji, and N. Ramanan

Abstract

This research article focuses on addressing the challenges associated with joining dissimilar metals through the application of solid-state welding techniques, specifically Friction Welding (FW). The study aims to develop optimal welding conditions, tools, and parameters for achieving a successful Aluminum–Steel (Al–Fe) butt joint. The resulting weld is extensively characterized through mechanical tests, microstructure analysis, and micro hardness measurements. Additionally, finite element analysis is conducted to simulate the behaviour of the prototype engine valve. The findings provide valuable insights into the feasibility and performance of friction welding for dissimilar metal joints, contributing to the further development and understanding of this welding technique.

Keywords

Characterization of dissimilar metals • Friction welding • Finite Element Analysis

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1 Introduction

Welding is a wonderfully adaptable and important procedure in the world of metalworking, serving as a skilled way to combine two distinct metal components using regulated heat. Its importance is felt across a wide range of sectors, where it not only ensures the assembly of sophisticated equipment and instruments, but also contributes to the construction of a plethora of critical structures and components. Because of its economic viability and widespread acceptance, the procedure has become a cornerstone of modern fabrication techniques. It is an art that involves a variety of processes, each precisely adapted to specific needs. To accomplish the necessary level of fusion, these strategies may include the use of gas torches releasing extreme heat or the strategic placement of external electrical supply. Welding emerges as a crucial method supporting various industries, whether it's the sophisticated accuracy necessary in automobile manufacturing, the aerospace domain with its demanding standards for aircraft and machinery frames, or even the sturdy building of railway waggons and boilers.

Furthermore, the impact of welding goes beyond original production and into critical maintenance and repair operations. Industries such as furniture manufacturing, structural work, and general machine maintenance rely largely on welding expertise to ensure the lifetime and reliability of their goods and equipment. Welding also plays an important role in secondary manufacturing processes, which are intricately linked to the development of refineries, oil tankers, and pipeline networks that propel the energy sector ahead.

Welding is based on the fundamental concept of physically connecting metal surfaces. This process entails the deliberate fusion of metals through controlled melting under external pressure, resulting in the development of a cohesive binding interface. Welding is a solid-phase joining method that has travelled through the ages, with a historical ancestry

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dating back around 3500 years to the rudimentary hammer welding procedures used by early blacksmiths.

Over ages, the art of welding has grown into a domain of varied approaches, each customized to unique purposes and limits. Brazing is a major contender among these techniques, relying on the idea of capillary action to suck molten filler material into the interstices of closely positioned metal surfaces, so cementing them into a cohesive whole. Meanwhile, friction welding is an innovation that capitalizes on the formation of heat by controlled mechanical friction, allowing metals to come together in a solid-phase state. Furthermore, reaching temperatures above 450 °C opens up the world of metal melting welding procedures, typified by operations involving controlled liquefaction followed by resolidification.

In place of traditional welding, a new technology known as soldering emerges, offering a parallel approach to material coalescence. Soldering makes use of a specialized alloy known as solder, which has a significantly lower melting point, frequently falling below the 450 °C mark. Unlike welding, which involves the metals themselves becoming molten, soldering works on the idea of aiding bonding through the liquefaction of the solder material. As the solder is carefully applied to the juncture during the soldering process, an intricate link is formed without the joined metals completely liquefying. This nuanced approach is especially important in situations where melting the base metals is either unwanted or impractical. Thus, soldering shows to be a flexible process, with applications spanning from electronics assembly to jewellery manufacturing.

The classification of weld techniques is inextricably linked to the intricacies of the joining process, which include aspects such as pressure application and the integration of filler materials. These parameters, taken together, determine how the connection is created and the resulting joint strength. Welding procedures range from those in which pressure is a critical component to those in which the addition of extra materials serves to reinforce and enhance the integrity of the connection.

Metal joining operations play a pivotal role across various sectors, demanding meticulous attention to material selection, techniques, safety protocols, and stringent quality standards (Li et al., 2016). In response to these challenges, the concept of solid-state welding emerges as a groundbreaking solution. It circumvents the need for complete material liquefaction by applying controlled pressure, inducing frictional heat, and meticulously maintaining temperatures beneath the melting threshold of the constituent materials. This innovative methodology serves as a direct response to the shortcomings inherent in fusion welding (Cai et al., 2019). When confronted with the task of amalgamating materials possessing disparate properties, the conventional method of fusion welding faces inherent limitations due to the hindrance imposed by their varying melting points. Consequently, this process may culminate in the formation of brittle intermetallic compounds (Mehta, 2019) The inherent adaptability of friction welding renders it an exceptionally promising solution across a myriad of industrial domains. Particularly in scenarios characterized by mass production necessitating metal joining, this technique shines as a beacon of innovation. Its unparalleled capability to forge steadfast connections between diverse materials, all while circumventing the limitations inherent in traditional fusion welding methods, underscores its transformative potential within the realm of modern industrial practices [4]. Friction welding (FW) exemplifies an exemplary paradigm of solid-state joining. This technique facilitates the fusion of materials by orchestrating rotational or translational motion between the workpieces through the application of precisely controlled compressive stresses. The ensuing kinetic energy generates heat, propelling plastic deformation and culminating in the establishment of a robust welding interface. Astonishingly, the efficacy of FW is achieved without the necessity for supplementary filler metals, flux, or shielding gases, thus amplifying its appeal and practicality (Maalekian, 2007).

The detailed study on joining of AA6061 (aluminum alloy) and AISI 4340 (low alloy steel) using continuous drive friction welding. Through metallographic examination, X-ray diffraction, electron probe microanalysis, tensile testing, and microhardness measurements, they found that dissimilar metal welds with a silver interlayer exhibited a maximum tensile strength of 240 MPa and 4.9% elongation. The presence of silver as an interlayer reduced the magnesium concentration at the weld interface by intermittently replacing it with silicon on the AA6061 side, limiting the interaction between iron and aluminum. The improved strength and ductility of these dissimilar metal welds were attributed to the formation of ductile phases such as Ag_3Fe_2, Ag_2Al, and Ag_3Al (Suresh & Meshram, 2015). Study on the continuous drive friction welding method used to solid-state join different materials, specifically AA6082 aluminium alloy and AISI 304 stainless steel. This process combines plastic deformation with heat produced by friction between two surfaces. Tensile testing, impact testing, Vickers micro hardness testing, fatigue testing, microstructural observation, and EDS measurements were among the tests and measurements used in the research of the welding process. The findings demonstrated that the austenitic stainless steel and aluminium parts' tensile strengths were greater than those of their respective base metals. As the friction time increased, the joint strength initially rose and subsequently fell after reaching a maximum value. The spectrum study of the alloying elements showed significant weight differences. The Steel-Al joints contained intermetallic compounds, according to EDX studies. In comparison to base metals, the hardness was increased close to the weld contact (Mohan & Gopi, 2017).

When endeavouring to unite steels with other materials through fusion welding processes, it becomes evident that unanticipated complexities can emerge. These challenges encompass a spectrum of potential issues, ranging from the propagation of unforeseen phases and vulnerability to grain boundary corrosion to the prospective emergence of delta and sigma ferrite phases at the weld interface. Particularly germane to scenarios where steel and aluminum constituents interplay within rotating systems and structural frameworks, the imperative to cultivate reliable, efficient, and economically viable joining methodologies is underscored (Chander et al., 2012). Against this backdrop of exigencies, the imposition of deliberate preventive measures assumes a paramount role. A notable tactical approach involves the judicious implementation of targeted heat treatments or the strategic adoption of accelerated welding speeds. These interventions wield the potential to markedly enhance the uniformity intrinsic to the welding interface. By adroitly choreographing the thermal kinetics and dynamics governing the welding process, a heightened degree of coherence and consistency can be achieved at the weld contact. This, in turn, substantiates the overarching structural soundness and operational efficacy of the assembled components (Padhy et al., 2015).

The experimental results indicated that the tensile strength of the welded material increased with an increase in upsetting force and heating time. The tensile strength also showed an initial increase with friction force up to a certain extent, but started decreasing when higher burn-off length, welding temperature, and flash were present. Optimal tensile strength was achieved at a friction force of $5 kN/mm^2$ and a heating time of 12 s. The variation of these parameters also had a relative effect on the hardness of the weld fusion zone and heat-affected zone (HAZ). In particular, specimen number 5 exhibited a hardness value of 85 and 88 in the fusion zone and HAZ, respectively, while specimen number 3 had a hardness value of 90 and 92 in the fusion zone and HAZ, respectively. These findings demonstrate that, for maximum weld strength, it is desirable to have minimum hardness values in the fusion zone and HAZ (Sriram Ravi Ramados, 2015).

Researchers focused on welding Austenitic stainless steel 304 and Aluminium alloy 6082 T6. Tensile tests were conducted on the welded samples, and the welding parameters were optimized using a design of experiments approach. The study aimed to analyse the effects of these parameters on the tensile strength of the joints in Aluminium alloy-Stainless steel welds. Experiments were carried out using various combinations of friction pressure, forging pressure, friction time, and forging time. The tensile strength of the welded joints was then analysed. The results revealed that increasing the friction time and forging pressures led to an increase in the tensile strength. However, beyond a certain point, further increases in these parameters resulted in a decrease in strength. Conversely, decreasing the friction pressure and forging time led to a decrease in the tensile strength. However, beyond a certain threshold, further decreases in these parameters resulted in an increase in strength. Microstructure analysis played a vital role in understanding the observed variations in tensile strength. Differences in grain structure were identified, which correlated with the higher and lower tensile strengths observed in the welded joints (Deepak Kumar & Venkatakrishnan, 2014).

In order to comprehend the effects, it was necessary to compare and contrast the microstructure, tensile strength, micro hardness, and FESEM-EDS results of welds with and without a nickel interlayer in the study on properties of friction welded joints between austenitic stainless steel 304 and medium carbon steel AISI 1040. The findings lead to a number of important conclusions. It was discovered that the forging pressure directly affected the ultimate tensile strength of welds without an interlayer, with the greatest strength of 636 MPa being attained at the highest forging pressure of 1.884 tonnes. The greatest strength of 661 MPa was nonetheless attained at the highest burn-off length of 8 mm when a nickel interlayer was added. When welding was done without an interlayer, peak hardness at the interface was 454 HV, but microhardness data showed a drop, registering 391 HV. This decline can be linked to nickel's presence at the contact, which inhibits the precipitation of chromium carbide (James & Sudhish, 1040). Authors focused on the evaluation of Flash Butt Welded Aluminium Copper transition Joints. They found that flash butt welded joints between aluminum–copper (Al–Cu) strips exhibited sufficient strength. However, the joint strength deteriorated significantly when subjected to heat treatment at 673 K for 20 h. This indicates that these joints may perform well for electric applications. Additionally, controlled bend tests revealed that the joints exhibited adequate ductility (Kumar et al., 2021).

The corrosion rate of chalcolithic copper, as evaluated by Tafel extrapolation technique in 3.5% NaCl solution, was only slightly greater than that of modern copper, according to authors who concentrated on the material characterization of ancient Indian copper. The existence of second phase sulphide inclusions has been suggested as the cause of the greater rate of corrosion in archaeological Cu (Srivastava & Balasubramaniam, 2003). Effects of intermetallic compounds on the mechanical and electrical characteristics of friction welded Cu/Al bimetallic joints during annealing have been the subject of research. As a result, the consequences of these qualities were examined when annealing. As a result, AlCu and $AlCu_2$ were found where intermetallic layers were being formed at joints (Lee & Bang, 2005). Friction welding of steel to steel, steel to aluminium, and aluminium to aluminium. Welding process temperature rise and transient heat generation were modelled. Over the weld zone, tensile testing and microhardness measurements were made. SEM was used to evaluate HAZ. The yield, tensile, and breaking strengths as well as the width of the heat-affected zone on the Al side are considerably impacted by the interaction of weld parameters for Al-steel welds, according to the results (Boopathy et al., 2019; Sahin et al., 1996).

The tensile strength and fatigue strength of commercial/tough pitch copper friction-weld joints have been examined using deformation heat input. The relationships between upset burn-off length, joint strength, and deformation heat input at the upset stage were studied for friction-weld joints made of 1050 pure aluminium and C110 tough pitch copper. Joint quality was evaluated using tensile and fatigue strength. Joint efficiencies of sound joints may be attained when the deformation heat input during the upset stage or the burn-off length exceeded a predetermined value (Boopathy et al., 2017).

2 Friction Welding Process

In the friction welding process, one workpiece remains motionless while the other rotates within the chuck of a specialized friction welding machine. As the two workpieces are squeezed together and forced to interlace, friction generates heat. The energy generated by frictional rubbing causes a significant temperature increase within the rubbing cross section of the workpieces, which is crucial for accomplishing successful forging during welding. When the rubbing cross section reaches the required forging temperature, the process undergoes a key change. The rotation of the workpieces is abruptly stopped, and the axial pressure exerted between them is increased at the same time. This critical phase incorporates a forging action into the equation, which culminates in the welding of the workpieces.

This forging method encourages molecular mixing and diffusion, resulting in a strong and seamless welded junction between the two workpieces. The specialized equipment used for friction welding resembles a lathe, which is a machine used to shape materials, but it is intrinsically more durable and engineered to withstand the extreme demands of the friction welding process. The capabilities of this apparatus are defined by two essential characteristics. To begin, it must be capable of achieving a high spindle speed, often exceeding 12,000 rpm, in order to promote the quick frictional creation of heat. Second, the equipment must be extremely durable in order to bear the significant axial pressure, which can reach 50,000 N/cm^2.

3 Pull Load Test

Tension testing, often known as pull load testing, is a vital cornerstone in the field of materials science. This critical method includes subjecting a specimen to regulated tensile forces until it fails. Figure 1 meticulously depicts the specimens designated for the pull load test, providing a palpable view into the experimental setup. The information acquired from these tension tests is crucial, fulfilling three functions. Primarily, it aids in the careful selection of materials for specific purposes, influencing design choices in a variety of industries. Furthermore, the results contribute to a strict quality control regimen, ensuring that materials adhere to set standards and tolerances. Furthermore, the test results play an important part in unravelling the intricate behaviour of materials when subjected to a variety of different stresses, hence improving our understanding of material reaction under various mechanical conditions.

The ultimate pull load strength is a vital signal, directly ascertainable through the pull load test, among the multitude of mechanical qualities determined through tension testing.

Fig. 1 Dissimilar weld joints

Table 1 Testing machine specification

S. no.	Parameter	Value
1	Load range	5 Tonne Max
2	Pull load specimen dimension	L = 100 mm, D = 20 mm
3	Bend test specimen Dimension	L = 150 mm, W = 16 mm, T = 20 mm
4	Izod test specimen dimension	
5	Make	Associated Scientific Engg. Works, New Delhi
6	Software details	FIE make India

This property contains the maximum magnitude of tensile force that a material can withstand before failing, providing critical insights into material robustness and longevity. Furthermore, the tension test reveals a slew of additional material properties. The maximal elongation, a measure of how far a material can stretch before breaking, is important in applications that require durability and flexibility. The computed area reduction reveals the degree of localized deformation, offering light on material ductility and formability.

4 Testing Specification

Pull load experiments are conducted using a Universal Testing Machine; Table 1 lists the equipment and specimen parameters. The variations for stress are compiled in Table 2.

The Universal Testing Machine (UTM) has established as the standard apparatus for performing Pull Load Testing, playing an important role in material testing and research. These machines, known for their versatility and widespread usage, include two separate types of crossheads that work together to simplify the complex testing procedure. One of these crossheads is meticulously calibrated to suit the test specimen's length, while the other works in unison to apply regulated strain on the specimen. The precision and accuracy of the testing method are supported by the coordinated interaction of crossheads. Within the field of Universal Testing Machines, two prominent varieties stand out: hydraulic and electromagnetic machines. Both of these iterations use their own systems to generate the forces required for pull load tests. The hydraulic-powered iteration uses the hydraulic principle to create tension, demonstrating its ability to administer forces with remarkable fidelity. The electromagnetic-powered equivalent, on the other hand, harnesses electromagnetic force creation, providing an alternate pathway for applying tension with exact control and efficiency.

In the context of these devices, a critical factor governs their testing suitability: capability. To arrange the pull load testing of a wide range of specimens, these devices must excel in four key areas: force capacity, speed, precision, and accuracy. A UTM's force capacity incorporates its ability to produce sufficient force to cause specimen breakdown, which is critical for replicating real-world circumstances and revealing material behaviour under stress. The force capacity, like the capability of a powerful engine, accelerates the UTM towards accurate replication of a specimen's response to applied forces (Ochi et al., 2003).

The machine's ultimate goal is to take accurate measurements of gauge lengths and applied forces. Precise positioning of the test specimen within the apparatus is critical to avoid unwanted bending forces generated by misalignment, which is especially important for brittle materials. This is mitigated by using spherical seats or U-joints between the grips and the machine. When the beginning segment of the stress–strain curve deviates from linearity, this is an indication of specimen misplacement. Extensometers are usually used to measure strains, although strain gauges can also be used to measure Poisson's ratio or microscopic specimens. Digital time, force, and elongation measuring systems are used in modern testing equipment, with electronic sensors attached to data acquisition instruments, which are often computers, and software for processing and outputting results. Notably, analog machines,

Table 2 Pull load test results

Stress, kN/mm^2	Strain
106	6.2
102	6.3
101	6.5
101	6.6
104	6.7
103	6.9

adhering to ASTM, NIST, and ASM metal pull load testing standards, persist due to their capability to surpass these benchmarks, substantiating their ongoing relevance in the field.

5 Micro Hardness Test

Utilized for assessing weld hardness, a Micro Hardness Tester assumes a pivotal role in this endeavour. The determination of hardness entails two distinct approaches: longitudinal assessment, encompassing hardness along the weld's length, and transverse measurement, spanning hardness across the weld's width. In meticulous detail, hardness values were meticulously recorded from the inception to the culmination of the weld. Moreover, the weld's hardness was gauged through a linear traverse parallel to the welding direction. The evaluation of relative hardness, synonymous with hardness joint efficiency, hinged on a comparative analysis between the weld's hardness values and those characteristic of its parent metal. In strict adherence to ASTM guidelines, the test specimens were meticulously fashioned, mirroring the protocol illustrated in Fig. 2.

Hardness Test Result for Different Zones is shown in Table 3.

6 Morphological and Simulation Analysis

6.1 SEM Analysis

Scanning Electron Microscopy (SEM) has emerged as a critical tool in the field of solid inorganic material characterization, allowing for precise microanalysis and failure studies. SEM reveals a treasure trove of insights into the microcosmic complexity of materials, proving helpful in unravelling the mysteries of material behaviour. High magnification imaging, an avenue via which elaborate landscapes of minute features and objects are methodically revealed, is at the forefront of SEM's capabilities. SEM, which operates in the nanoscale domain, provides high-resolution pictures that serve as windows into the hidden regions of material structures. Furthermore, this approach isn't limited to just visual documentation; it also includes quantitative assessments that allow for the precise measurement of even the most insignificant qualities.

The coordination of a focused stream of high-energy electrons is the underlying premise of SEM. This electron beam, like a virtuoso's baton, choreographs an elaborate dance across the surface of solid objects, producing a symphony of interactions that produce a variety of signals. These signals are expertly manipulated to extract a lot of information. They provide information on topography, elemental composition, and even crystallographic orientation. Such diverse studies are a veritable toolkit for investigating the inner topography of materials. In practice, SEM is frequently used to scan across a specific section of a sample's surface. The data gathered from this spatial excursion is then skillfully put together to create a two-dimensional image. This image is a visual tapestry rich in detail, depicting differences in features that cover a wide range of aspects, from the specific fingerprint of chemical composition to the texture that characterizes the material's individuality.

To investigate the phases that form the welding interface, scanning electron microscopy and energy dispersive analysis of X-rays (EDAX) analyses were used. An energy dispersive analysis of X-rays (EDAX) study in conjunction with a 20 kV field effect scanning electron microscope was used to record the observations. The programme allows for beam piloting to scan along a surface or a line to produce X-ray mapping or element-specific concentration profiles. The interface zone in the friction welded joint between EN24 STEEL and AL6061 has a SEM microstructure.

The four layers' average grain sizes are as follows: BM > HAZ > TMAZ > NZ. BM (Base Metal, consisting of AL6061 and EN24 steel), TMAZ (Thermo mechanical

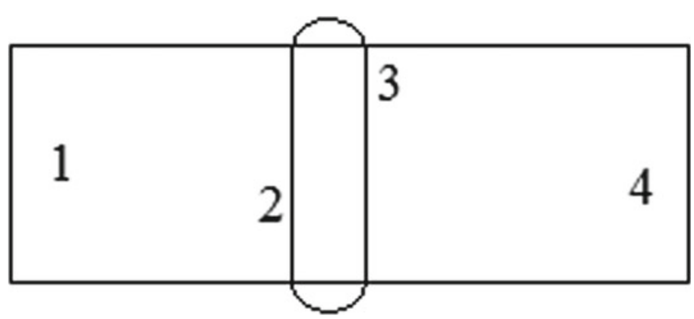

Fig. 2 Micro hardness test setup. 1. Zone of parent material Al.alloy 6061. 3. Zone of parent material EN24. 2. Zone of Al.alloy 6061 near the weld. 4. Zone of EN24 Steel near the weld

Table 3 Hardness test result for different zones

Sample no.	Zone-1	Zone-2	Zone-3	Zone-4
1	95.8	93.8	85.2	91.1
2	58.8	62.2	63.3	65.5
3	91.2	93.3	94.2	95.7
4	37.8	35.5	36.6	37.4
5	56.6	57.8	55.5	58.2
6	53.3	54.2	52.2	51.5

impacted zone), HAZ (Heat affected zone), and NZ (Nugget zone) are the four main FW zones that can be seen from Fig. 3. The base metal exhibits an agglomerate-like microstructure with lengthy grain sizes. Due to the homogenous nature of the entire region and the dispersion of such grains' crystal orientations, the tensile strength is affected by small grain size. The TMAZ area experiences plastic deformation, but because the deformation strain was insufficient, recrystallization did not occur there. The aluminium alloy underwent a heat cycle in HAZ, although minor plastic deformation happened. Thus, the tensile strength was reduced as grain size increased. The dislocation movement in the material will have an impact on the tensile strength as the grain size decreases. Due to the metal's plastic hardness to flex, minimizing grain dislocation movement (fine grain size) can increase the material's mechanical strength.

6.2 Simulation Analysis

The interaction (coupling) between two or more different types of phenomena (fields) is taken into account in a coupled-field analysis. (Boopathy et al., 2021) The fields involved in these assessments may be coupled directly or indirectly. ANSYS components that can be used in direct-coupled-field analyses are listed below and the captured image of stress variations depicted in Fig. 4 and Fig. 5 respectively. Thermal DOF is not present in all elements. An analysis that is directly connected computes DOF from numerous fields at once. The Direct Method, as it is known, is only required when the model's individual field responses depend on one another. Since the equilibrium condition must be met according to numerous criteria, directly coupled analyses are typically nonlinear. Matrix equations are larger and more expensive to analyse for multi-field models of comparable size because there are more DOF active per node.

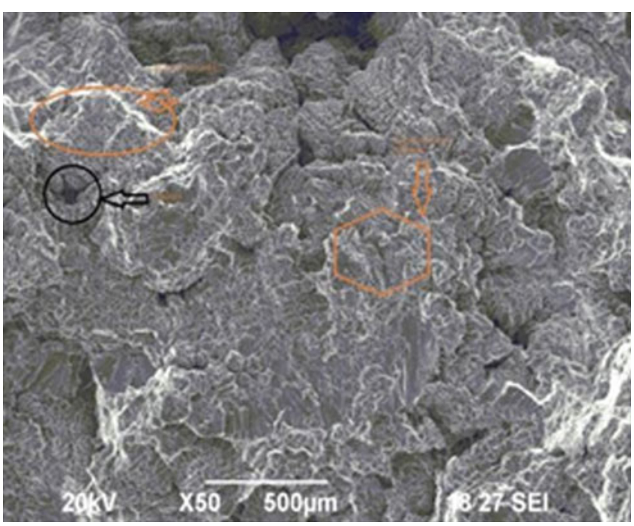

Fig. 3 Weld zone fracture surfaces

7 Conclusion

The difficulties of combining different metals, notably Aluminum and Steel, have been solved in this study article through the use of solid-state welding techniques like Friction Welding. The best welding setups, equipment, and settings have been created via considerable experimentation and analysis in order to produce good butt joins between aluminum and steel. Through mechanical tests, microstructure analysis, and measurements of the welds' hardness at the microscopic level, the finished joints have been fully characterized. The results of this investigation offer important new information about friction welding's performance and viability for joining dissimilar metals. The study emphasizes the significance of welding process optimization for producing durable junctions between steel and aluminum. Furthermore, the finite element study performed on the prototype engine valve has given researchers a better knowledge of how the weld will behave and perform under actual operating circumstances. The insights gathered from this research can direct future developments in welding technology and make it easier to successfully combine metals that are different from one another, creating new opportunities for a variety of industries and applications.

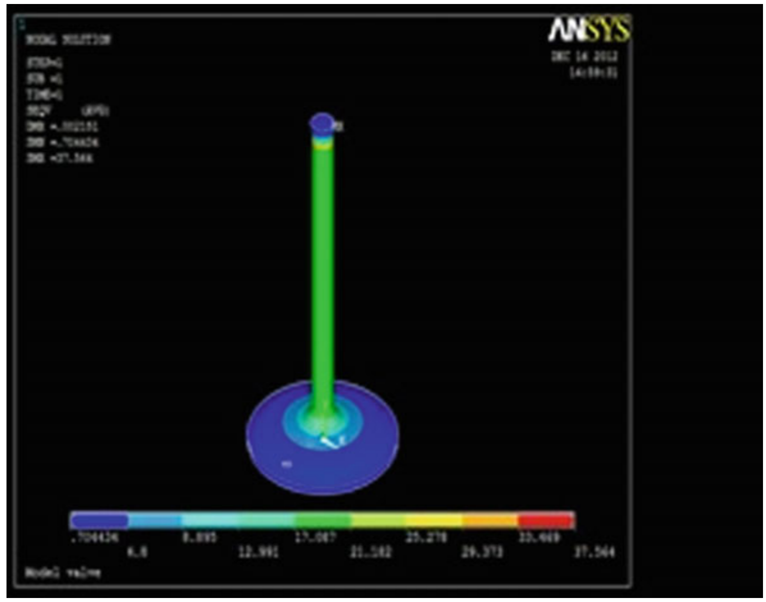

Fig. 4 Stress distribution

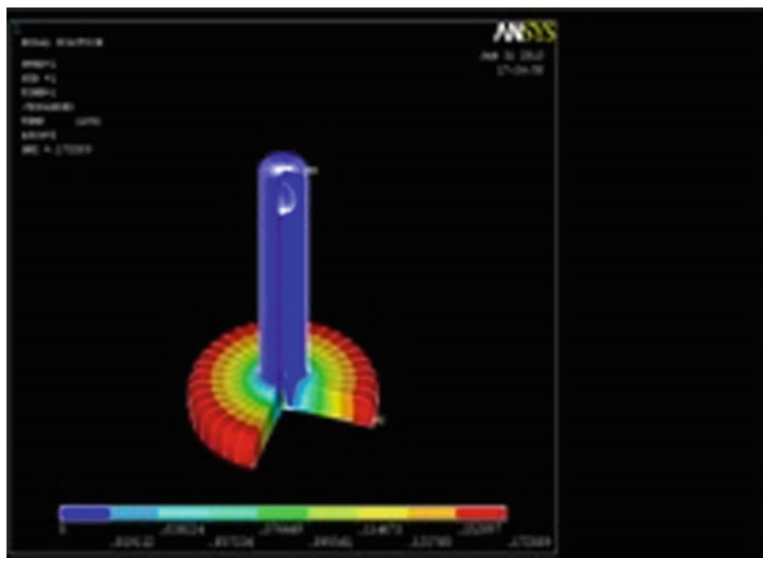

Fig. 5 Strain variations

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