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Transient Thermal and Microstructural Analysis of Friction Welded Joints Made Between INCONEL 800 and AISI 304

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Abstract
Friction welding is a solid state welding process capable of joining similar and dissimilar material combinations. The Inconel 800 and AISI 304 stainless steel was friction welded at three rotational speeds 1300, 1400 and 1500 rpm, friction time was varied as 3, 4 and, 5 sec, friction pressure was maintained at 99.92, 124.9 and, 156.13 MPa, and forging pressure was kept at 156.13 MPa. The maximum tensile strength of the friction welded Inconel 800 and AISI 304 stainless steel was 548.3 MPa for the samples processed at a rotational speed of 1500 rpm, friction time 4sec, friction pressure of 99.2 MPa and a forging pressure of 156.13MPa. An inseparable well mixed plasticized zone with recrystallized zone was observed at the interface. The optical micrographs revealed the presence of austenite phase, along the grain boundaries fine spherical carbides and intermetallic compounds. The width of the plasticized and recrystallized zone at the interface was more for the annealing heat-treated samples. The temperature profile obtained after thermal analysis using ANSYS software had given a maximum temperature of 950°C and away from the interface at the edge of the base metals it was a minimum of 36.5 °C.

Keywords: Friction welding; INCONEL 800; AISI 304; dissimilar weld; micrograph; tensile strength; ANSYS; thermal analysis

Introduction

Inconel alloy possess good corrosion, heat resistance and strength, because of these superior properties this alloy finds wider application in thermal, nuclear power plants and in heat-treatment industry. Kim et al [1] reported Inconel 800 super alloy containing major alloying elements such as 32% Ni, 23% Cr and 40% Fe. Luo et al [2] stated the pipes used in nuclear power plants are generally fabricated from austenitic stainless steels, because they possess good formability, mechanical properties. Friction welding is a solid state welding process capable of joining similar and dissimilar material combinations. Avinash Pachal et al [3] disclosed that in friction welding, the joints are formed in the solid state by utilizing the heat generated by friction. During friction welding, two parts are brought together to maintain contact between them, among the two parts, one of the joint species is rotating at a particular speed and the other one is stationary. The two surfaces in contact generate heat because of frictional forces acting between them. This force is directly proportionate to the process parameters such as contact pressure, rotational speed and contact time. Mumim Sahin et al [4] designed a friction welding set-up and successfully joined high speed steel and medium carbon steel.

Shubhavardhan and Surendran [5] performed friction welding with the dissimilar metal combination aluminium alloy and AISI 304. The optimum parameters were obtained by conducting experiments with orthogonal array L9 and analyzed the data. Gourav Sardana and Ajay Kumar [6] studied and assessed the development of solid state joints of dissimilar material HSS M33 and AISI 316 stainless steel, via continuous drive friction welding process, which combines the heat generated from friction between two surfaces and plastic deformation. Hussein Mesmari and Fawzia Krayem [7] analyzed the mechanical and microstructure properties of 304 stainless steel friction welded joint. Sathiya et al [8] investigated the effect of friction welding parameters on mechanical and metallurgical properties of ferritic stainless steel. Satyanarayana et al [9] investigated on continuous drive friction welding of austenitic-ferritic stainless steel combination. Vishnu and Sujith Joseph [10] predicted the optimum friction welding parameters for joining medium carbon steel using surface response methodology. Paventhan et al [11] reported a maximum tensile strength of 543 MPa for the joints made between carbon steel and stainless steel under the welding conditions, 90 MPa of friction pressure, 6 s of friction time, and 6 s of forging time. Friction pressure was found to have greater influence on tensile strength of the joints, followed by friction time, forging time, and forging pressure.

The high temperature produced at the joint region within short time during the friction welding plays a vital role for good strength and joint efficiency. The heat input is directly proportionate to the speed, axial pressure and size of the job. The joints which are exposed to higher temperature exhibit the deleterious effect of flash formation and increase in width of the interface at the joint region. This may benefit or impart adverse effects on post heat treated welded joints. In the present work the effect of post heat treatment on joint strength and metallurgical characteristics such as increase in width of interface and coarsening of the compounds are studied. The conductive heat transfer from the joint region towards the base metal is estimated, which is an important study to understand the joint quality and flash formation. The transient thermal analysis is performed using ANSYS software and the results are presented.

Experimental Work

Friction welding of AISI 304L with INCIONEL 800 was carried out with the equipment available in Annamalai University. A photograph of the friction welding equipment is shown in Figure 1 (a). The friction welding parameters and experimental order maintained while conducting the experiments were given in Table 1.

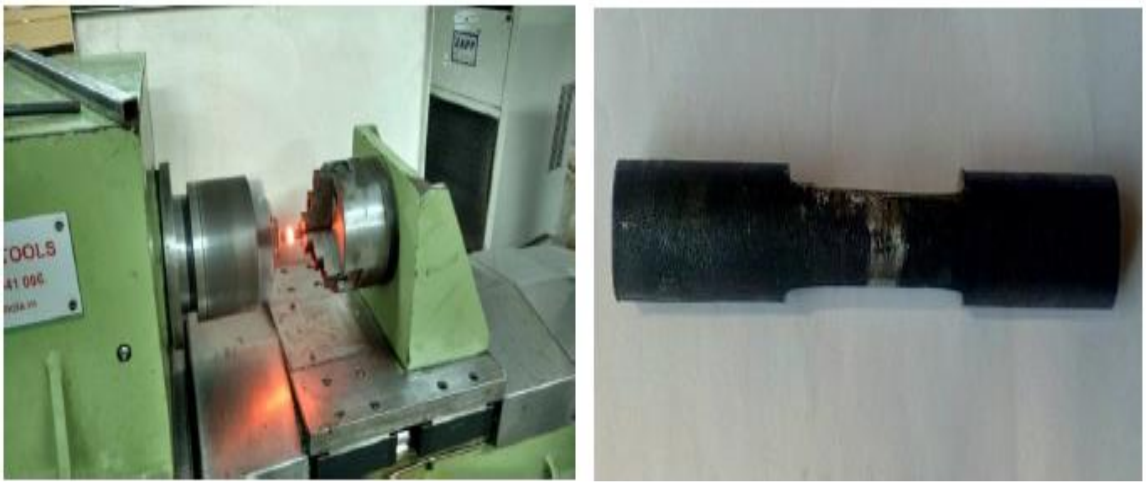

Fig.1 (a) A photograph of the rotary friction welding equipment and (b) A photograph showing the tensile test specimen.

The welded samples were machined in a lathe to obtain tensile test specimens of 150 mm in length and diameter 10 mm and metallography specimens of size 30 mm in length and diameter 10 mm with a flat surface 5 mm on top surface was produced by performing grinding operation. The tensile test specimens were prepared as per ASTM E8M and shown in Figure 1 (b). The tensile test was conducted with a computerized tensile testing machine. The metallography specimen was prepared by finishing with various grades of abrasive sheets such as 220, 320, 400, 600, 800, 1000 and 1200 and finally polished with slurry of Al_2O_3 for two minutes. The polished specimens were etched with a chemical mixture containing 50 ml Hydrochloric acid (HCl), 15ml Nitric Acid (HNO_3), and 5 ml Glycergia water (H_2O) and 2 drops of Hydro fluric acid. The etch products were not removed from the surface of the metallography specimens. The specimens were examined with Olympus inverted type of microscope

Table 1: Chemical composition of the base metals.

Material	P%	Ti%	Al%	C%	Si%	Mn%	Mo%	Ni%	Cr%	Fe%
INCONEL 800	0.03	0.40	.0.50	0.10	-	-	3.5	32	23	39.5
AISI 304	0.06	-	-	0.08	0.9	1	0.2	8.4	17	Balance

Table 2: Experimental conditions and performance parameter.

Sample	Rotational speed (Rpm)	Friction time (sec)	Friction pressure (Mpa)	Forging pressure (Mpa)	Tensile strength (Mpa)
1	1300	3	99.2	99.92	512
2	1300	4	124.9	124.9	514.4
3	1300	5	156.13	156.13	518.2
4	1400	3	124.9	156.13	524.6
5	1400	4	156.13	99.92	530.3
6	1400	5	99.92	124.9	530.7
7	1500	3	156.13	124.9	544.3
8	1500	4	99.92	156.13	548.3
9	1500	5	124.9	99.92	546

Modeling and Heat Input Calculations

A solid 3D model of the friction weld joint with which analysis is performed was created. The 3D model was created using 3-D primitives known as volumes. Model dimensions were created using Cartesian coordinate system. During modeling a working plane was created, further, a movable reference plane was used to locate and orient modeling entities. Loads were applied on the solid model areas. The transient thermal analysis was performed using ANSYS software. Transient thermal analysis was used to determine temperatures and other thermal quantities that vary over time.

During friction welding of dissimilar metals heat is generated by converting the mechanical energy into thermal energy at the interface of the work pieces by rotating Inconel 800 circular 10 mm diameter work piece against a stationary AISI 304 circular work piece of 10 mm in diameter which exerts contact pressure on the rotating specimen. The heat flux is calculated using the equations given in the literature published by Ahmet Can et al [12]. The parameters used for calculating the heat generated and the calculated values are tabulated in the Table 3.

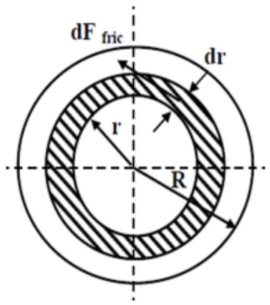

Fig. 2: An elemental ring on the friction surface.

Consider an elemental ring of thick 'dr' at a distance 'r' from the centre. The elemental ring when it is rotating and rubbing on a similar contact surface frictional force of 'dF_{fric}' is developed, because these two surfaces are in contact with a contact force'P'.

$$\int_0^R dQ = 2\pi\mu P\omega r^2\, dr \qquad 1$$

$$Q = 2\pi\mu P\omega \frac{R^3}{3} \text{ Watt} \qquad 2$$

$$Q = \frac{2}{3}\pi\mu P\omega\, R^3 \text{ Watt} \qquad 3$$

$$M_{Tf} = \int_0^R 2\pi\mu P r^2 dr \qquad 4$$

$$M_{Tf} = \frac{2}{3}\pi\mu P\pi R^3 \qquad 5$$

$$Q = \omega\, M_{Tf} \quad \text{Watt} \qquad 6$$

Then, heat generated in unit time over the friction surface is equal to total torque multiplied by angular velocity as given in equation 6. Therefore, the Heat flux occurred at any point of the circular section at distance 'r' form the rotation axis is calculated as given in equations 8 and 9

$$q = \frac{dQ}{(2\pi r dr)} \qquad 7$$

$$q = \frac{2\pi\mu\omega P r^2 dr}{2\pi r dr} \text{ Watt/m}^2 \qquad 8$$

Finally, the heat flux developed over any point at distance 'r' from rotation axis is given as

$$q = \mu\omega Pr \quad Watt/m^2 \qquad 9$$

Where

$dA = 2\pi r dr$ Area of he elemntal ring

M_{Tf} – Frictional torque

P – Pressure due to contact force in N/m^2

μ – Coefficient of friction between the two metal surfac

ω – Angular velocity rad/s

R, r – Radius of the friction welded bar

Q – Heat generated in Watt

q – Heat flux in $Watt/m^2$

Table 3: Heat generated at the Inconel 800-Stainless steel 304L interface.

Level	Speed r.p.m	Friction pressure MPa	Forging pressure MPa	Friction time in sec	Load N	μ	Ang.vel rad/sec	Radius in m	Heat generated Watts/m²
Low	1300	99.92	156.13	3	2000	03	136.07	0.005	204×10^5
Medium	1400	124.9	156.13	4	2000	03	146.53	0.005	275×10^5
High	1500	156.13	156.13	5	2000	03	157.00	0.005	368×10^5

Results and Discussions

Optical Microscopy

The optical micrographs shown in Figure 3 (a) reveals the base metal Inconel 800 microstructure of the friction welded, non heat-treated samples processed at a rotational speed of 1500 Rpm, friction time 4 sec,friction pressure of 99.2 MPa and forging pressure of 156.13 MPa. Very fine grains are seen in the micrograph. Also, presence of intermetallic compounds and secondary phase particles are noted throughout the matrix. The micrograph shown in Figure 3 (b) is taken at higher magnification for the sample heat-treated at 950 ºC for 1 hour. The micrograph reveals the presence of austenite phase, along the grain boundaries fine spherical carbides and intermetallic compounds. These tiny green spheres are present throughout the matrix. The micrograph shown in Figure 4 is for the base metal AISI 304L. At several places annealing twins are seen along with austenite grains. Also, at several places along the grain boundaries tiny spherical carbides are seen, these carbides are precipitated along the grain boundaries. At few places large spherical balls are seen, these spheres are presumed to be carbides in the base metal stainless steel. Mumin Sahin [13] observed the microstructure of the austenitic stainless steel was elongated along the deformation direction. Further, recrystallized grains were observed in the joint region because of plasticized metal formed during friction welding.

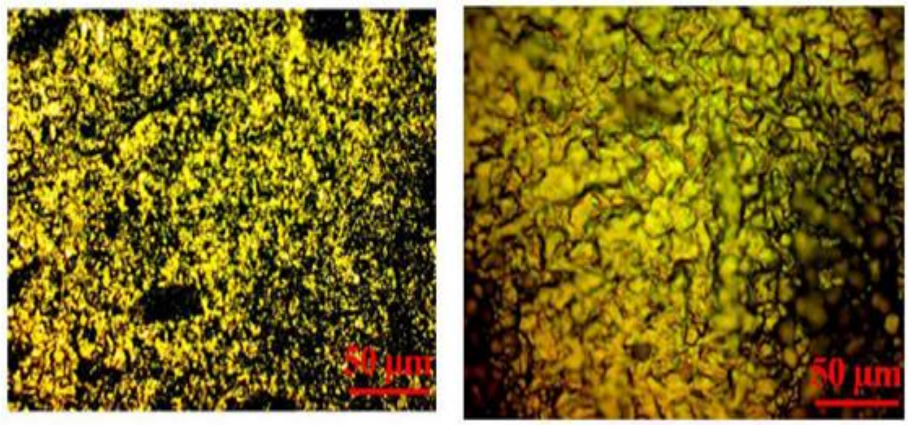

Fig.3: (a) Optical microstructure base metal Inconel 800 and (b) microstructure of the heat-treated base metal Inconel 800.

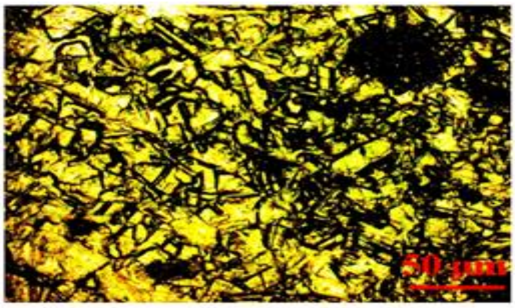

Fig. 4: Optical microstructure of the base metal AISI 304L.

to the friction welded, non heat-treated samples processed at a rotational speed of 1500 rpm, friction time 4sec, friction pressure of 99.2 MPa and forging pressure of 156.13MPa. A dark thin interface is seen between the base metal Inconel 800 and AISI 304L stainless steel. On the stainless steel side, yellowish grains are seen and these grains are austenite grains.

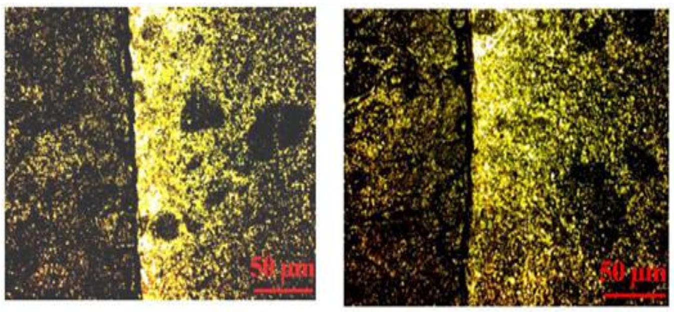

Fig. 5: (a) Optical microstructure of the friction welded sample and (b) Optical microstructure of the friction welded heat-treated sample.

Very close to the interface on both sides of the base metal very fine grains are seen. The reason for very fine grains is attributed to recrystallization of the base metals during friction welding. During friction welding at the interface temperature rises above the recrstallization temperature, therefore, the plasticized base metals form a homogeneous mixture and form a recrystallized zone. Meshram et al [14] friction welded pure Fe–Ni rods and reported the presence of intermetallic compound Fe-Ni in the friction welded joint.

In the micrograph 5 (b) a thick interface is seen between the base metal Inconel 800 and AISI 304L stainless steel. The thickness of the interface is greater than the one observed in the Figure 5 (a). On the stainless steel side yellowish grains are seen and these grains are austenite grains. Very close to the interface on both sides of the base metal very fine grains are seen. The fine grains adjacent to the stainless steel are darker than the one observed in Figure 5 (a), for the non heat-treated sample. This indicates diffusion of elements from the concentration rich base metal Inconel 800 to the AISI 304L during 1 hour annealing. Further, presence of fine grains is attributed to diffusion and recrystallization during annealing heat-treatment performed on the sample. In the weld zone fine grains are observed as seen in Fig 5 (b) and in the thermo-mechanically affected zone curved flow lines of the plasticized metal are seen. The above mentioned observations are made in the literature published by Preuss et al [15].

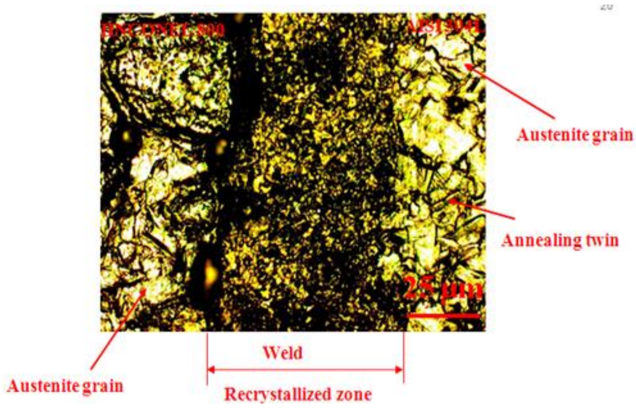

Fig.6: Optical microstructure of the friction welded heat-treated sample at 1000 X.

The micrograph shown in Figure 6 corresponds to the heat-treated sample taken at a magnification of 1000 X. The width of the recrystallized zone is roughly 75 microns for the heat-treated samples. In this mushy zone, dark and yellow grains are seen. The yellow grains indicate the presence of austenite grains. These recrystallized grains are very fine compared to the grains seen adjacent to this zone in the base metal regions. The interface is inseparable and defect free. Closer to the interface along the base metal Inconel 800 very large grains are seen. Along the grain boundaries precipitation of secondary phase particles and inter metallic compounds are seen. Precipitation of intermetallic compounds were reported int eh work done by

Preuss et al [15]. At one or two places spherical carbides are present along the grain boundaries and grain boundary triple points. On the other side of the micrograph yellow austenite grains are seen, these grains are larger than the one found in non heat-treated samples.

Tensile Test

The tensile strength of the friction welded samples processed at various conditions are tabulated in Table 4. For the sample friction welded at a rotational speed of 1500 rpm, friction time 4sec, friction pressure of 99.2 MPa and forging pressure of 156.13MPa and heat-treated for 1 hour yielded a maximum tensile strength of 548.3 MPa. Preuss et al [15] reported reduced hoop stress in the friction welded super alloys after post weld heat-treatment. The tensile strength of the joints was very close to the base metal strength.

Table 4: Experimental conditions and tensile strength of the joints.

Sample	Rotational speed (Rpm)	Friction time (sec)	Friction pressure (Mpa)	Forging pressure (Mpa)	Tensile strength (Mpa)	S/N ratio	Mean
1	1300	3	99.2	99.92	512	54.1854	512.0
2	1300	4	124.9	124.9	514.4	54.2260	514.4
3	1300	5	156.13	156.13	518.2	54.2899	518.2
4	1400	3	124.9	156.13	524.6	54.3966	524.6
5	1400	4	156.13	99.92	530.3	54.4904	530.3
6	1400	5	99.92	124.9	530.7	54.4970	530.7
7	1500	3	156.13	124.9	544.3	54.7168	544.3
8	1500	4	99.92	156.13	548.3	54.7804	548.3
9	1500	5	124.9	99.92	546	54.7439	546.0

The fracture took place at the base metal Inconel 800 and is ductile in nature. A minimum tensile strength of 512 MPa was recorded for the sample friction welded at a rotational speed of 1300 rpm, friction time 3sec, friction pressure of 99.2 MPa and forging pressure of 99.2 MPa. The decrease in tensile strength is attributed to low heating time, low and low forging pressure.

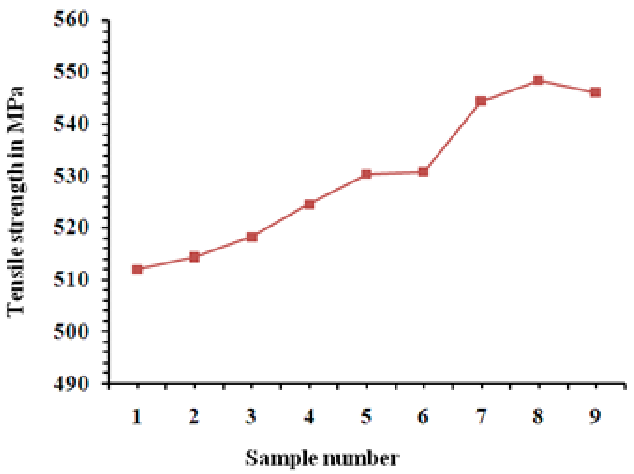

Fig. 7: A graphical plot between sample number and tensile strength.

Using statistical software minitab17 software, Taguchi's L9 orthogonal array is analysed and the results are given in Table 4. The optimum parameters for the stainless steel Inconel joints is rotational speed of 1500 Rpm, friction time 4sec, friction pressure of 99.2 MPa and forging pressure of 156.13 MPa. The Signal to Noise ratio is 54.7804 which is maximum for the above set parameters. Further the Mean value 548.3 is the maximum among the observed values for all the other processing conditions. The graphical plot between level and Signal to Noise ratio is shown in Fig. 8.10. Another graphical plot between Level and Mean Tensile strength is shown in Fig 7. Anand and Tamilmannan [16] optimized the friction welding parameters for the Incoloy 800 H using desirability function analysis of Taguchi.

Transient thermal analysis

The transient thermal analysis performed with ANSYS software is presented as a graph giving details of temperature distribution of the welded joint. The temperature distribution is shown in Figure 8. The temperature profile indicates that at the centerline of the weld it is maximum and as the distance increases away from the centerline it decreases. The maximum temperature is 950°C and it is minimum of 36.5 °C at the other side of the base metals from the interface. The peak temperature in the joint is at least between 850 and 950 °C which conform to the published work of Wang et al [17]. The experimental values, theoretical calculations on temperature distribution and thermal analysis performed with ANSYS software are comparable.

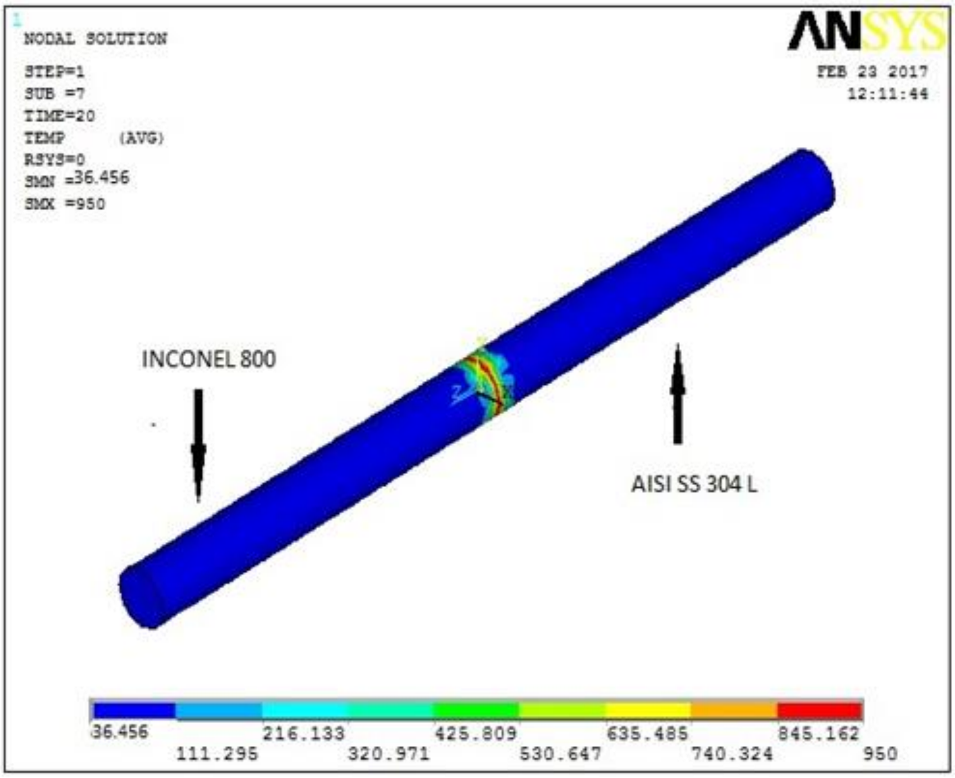

Fig.8: The transient thermal analysis of the friction welded specimen.

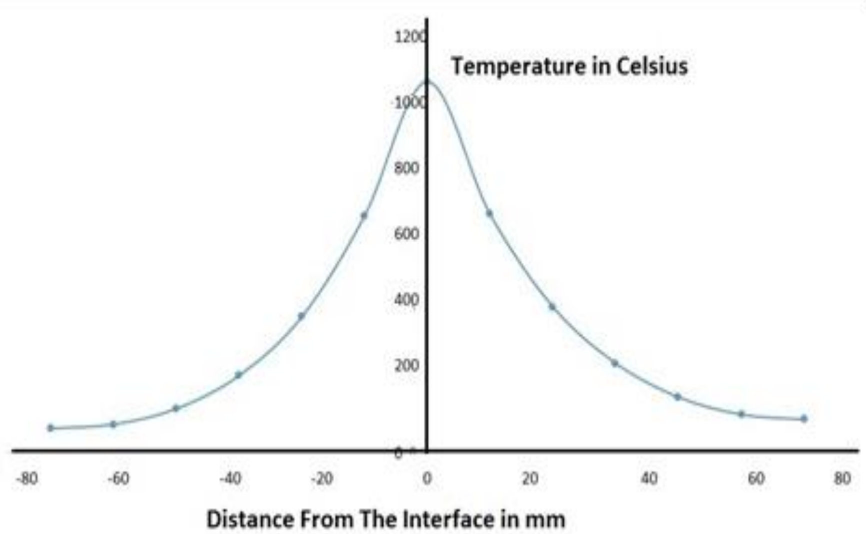

Fig.9: A graphical plot between distance vs Temperature from the interface.

These values are almost similar and the difference is less than 10% of the maximum value recorded at the interface where heat is generated because of friction. The temperature distribution with respect to time is studied and it is found that the maximum temperature is 1050°C and the minimum temperature in the rod region is 36.5°C. Wang et al [17] performed inertia friction welding of Ni based super alloy and observed that the interface temperature was 940 °C within 1 sec. The width of the hot zone was on the rise with respect to rise in friction time. After 4 sec the interface temperature was a maximum of 1200-1300°C. In the current work the interface temperature is only 1100 °C. The reason for decrease in temperature is attributed to dissimilar metal combination AISI 304 and Inconel 800. The Figure 9 gives the calculated values of temperature at various points on both sides of the friction welded specimen.

Conclusions

- Friction welding of INCONEL 800 and AISI SS304L was successfully carried out. The welded joints revealed a good bonding between the two base metals.
- The joint strength is nearly 98% of the base metal AISI SS304L strength.
- Heat treated samples revealed a tensile strength of 580 MPa.
- The temperature distribution with respect to time is studied and it is found that the maximum temperature is 1050°C and the minimum temperature in the rod region is 36.5°C.

- Thermal analysis was performed using ANSYS software. The theoretically calculated values and values obtained using ANSYS software are almost equal.

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