Heat Flow Simulation and Evolution of Microstructure in Welding of Rail Steel

K. Biju, K. Narayan Prabhu and K. Rajendra Udupa
Department of Metallurgical & Materials Engineering
National Institute of Technology Karnataka Surathkal Mangalore

ABSTRACT

In the present study heat flow simulation was carried out to predict the microstructure and examine the effect of preheat and plate thickness on cooling rate of the weld metal. SOLIDCAST software is used for simulating thermal regime in the base metal. The results of simulation studies revealed that cooling rate and hence the evolution of microstructure along the parent metal were functions of the preheating temperature and the plate thickness. The superimposed simulated temperatures on CCT diagram indicated the absence of martensite precipitation in HAZ region and this was experimentally verified. The results also indicated the possibility of suggesting the preheating temperature for defect-free welding of plates of given thickness.

INTRODUCTION

Fusion welding is of great importance in the fabrication of engineering structures. It involves the deposition of a small amount of molten steel within a gap between the components to be joined. When steel solidifies, it joins the components together. Three metallurgical zones, namely, fusion zone, heat affected zone and base metal zone, are identified in the plate upon completion of the welding. The peak temperature and subsequent cooling rate determine the HAZ structure whereas thermal gradients in the liquid pool, solidification and cooling rates at the liquid-solid pool boundary determine the solidification structure in the fusion zone. A fusion welding process involves heat flow through the base metal during welding to accomplish the desired joint. Depending upon the heating and cooling cycles, different types of microstructures are obtained in weld bead and heat affected zone. This leads to varying mechanical properties in the metal. Hence it is essential to assess the effect of heat flow during welding on metallurgical microstructure [1]. This can be achieved by the use of computer simulation technique, where the microstructure of weld before conducting actual welding can be reasonably predicted. Based on this prediction suitable modifications can be made at the design stage itself to produce a good weld structure. Further, the simulation results would be useful in predicting variations in the thermal cycle within the weld metal, which is very important, since the temperature distribution in the base metal controls the final structure and mechanical properties. Fujitha et al described a new system for computing thermal histories to predict the properties of welded joints using the CCT diagrams data base [2]. 2D and 3D finite-element models were developed by Wahab et al. using the solution of heat-transfer equations [3]. The accuracy of the predicted cooling times, weld penetrations and the lengths of the weld pools were compared with experimentally obtained values for bead-on-plate welds. A mechanical weld pool ejection rig developed in this study provided a quick and ready means of defining a full 3D weld-pool shape. Kim et al studied the temperature profiles, weld pool shape and size, and the nature of the solidified weld pool reinforcement surface during gasmetal arc (GMA) welding of fillet joints using a three-dimensional numerical heat transfer model [4]. Chan modeled the heat transfer mechanism involved in the welding process and developed a software to simulate the pulsed arc welding of thin plate in which the heat input is from the weld arc to the weld workpiece [5]. Realistic thermal boundary conditions including convection, radiation, the latent-heat effect during phase change and other welding parameters, were taken into consideration to predict temperature fields around the weld pool. A computer program was developed by M. Hang based on the computation model for quasi-steady heat transfer problems of welding with the boundary element method [6]. The model was used for the computation of thermal cycles at heat affected zones with gas shielded metal arc welding (GMAW) on medium thickness plates. A computational procedure was suggested by Deng and Murakawa for analyzing temperature fields and residual stress states in multi-pass welds in SUS304 stainless steel pipe [7].

Effect of plate thickness on mechanical properties of arc welded steel joints was investigated by Shehata [8]. The results showed that joint strengths vary according to plate thickness and the distance from the weld root.

Cooling rate plays an important role in welding. It controls the final microstructure. If the cooling rate is very high, hard brittle structure forms which results in the formation of cracks in the weld. This problem can be effectively controlled by preheating the plates to be welded. Preheating reduces not only the cooling rate of weld and HAZ, but also the energy required to deposit a given weld. Another factor that affects the cooling rate is thickness of plates to be joined. As the cooling rate dictates final microstructure, the plate thickness also has significant effect on the microstructure.

Voltage	50V
Current	87 amp
Time to complete welding	62 s
Electrode Used	E6013
Welding Speed	1048 mm/s

Table 1 : gives the welding parameters.

Rails are designed to resist wear and rolling contact fatigue and thermal stress caused due to temperature variations. Especially in the contact zone, rail steel should have good mechanical properties like yield strength, tensile strength, toughness and wear resistance. The present study involves analysis of the effect of plate thickness and preheat temperature on the cooling rate in a weld and prediction of final microstructure in the HAZ using simulated thermal data and CCT diagram of the base metal.

EXPERIMENTAL

The material used in this study was a 105 x 65 x 9 mm thick plate of rail steel (% C: 0.6-0.8).

A schematic sketch of the experimental set-up is shown in Figure 1. Two K type thermocouples TC1 & TC2 were inserted in the specimen at locations 9 mm and 60 mm from the weld centerline. Two 0.5mm holes were drilled horizontally from the side of the groove in order to insert the thermocouples. Welding operation was performed using a manual metal arc welding process.

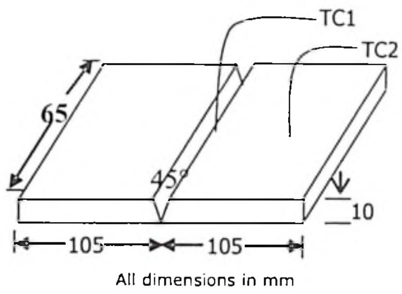

Figure 1: Schematic sketch of weld plates instrumented with thermocouples

Before welding, the base plates were mechanically ground to remove the rust and a V-groove is incorporated.

A coated electrode type E 6013 was used as a filler material. The data logger is activated at the time of welding.

The welding operation was started along the V-groove. The thermocouple and the work piece were shielded with ceramic insulating sleeve to reduce heat transfer through the surface by convection and radiation.

Temperature measurements were recorded via an off-line data logger.

Thermal conductivity	49.9 W/mK
Specific Heat	489 J/kgK
Density	7822 kg/m^3
Initial Temperature	2500°C
Solidification Temperature	1368°C
Freezing Range	108°C
Latent Heat of Fusion	270 kJ/kg
Fill Time	62 s

Table 2 : Properties of parent metal used in simulation

After experimentation, weld samples were sectioned, polished and etched using 3% nital for micro-examination.

NUMERICAL SIMULATION

Numerical experimentation was conducted by using SOLIDCast simulation software [9]. SOLIDCAST software is based on finite difference numerical method. This software is generally used for thermal analysis of castings. Welding is a casting process in miniature and the base metal was assumed as the mold and weldment as the casting. The main difference between casting and welding is the difference in the solidification process. In the case of casting the solidification occurs by nucleation and growth. But in the case of welding it is due to the epitaxial growth. The thermophysical properties of the weldment and parent metal are given in Table 2 and Table 3 respectively.

Initial Temperature	30°C
Thermal Conductivity	49 W/m-k
Specific Heat	489 J/kg K
Density	7822 kg/m^3

Table 3 : Properties of weldment used in simulation

While thermal properties of the materials are used to calculate heat flow within a given material, heat transfer coefficients allow assessment of heat transfer at the interface between two materials. Heat-Transfer Coefficient (HTC) is an indicator of how well an interface between two materials can conduct heat. It is not a property of a material but a property of the surfaces in contact. Table 4 gives the values of heat transfer coefficients used in the present simulation. Virtual thermocouples were inserted in the model before conducting simulation.

Interface	h W/m^{2}K
Weldment/ambient	150
Parent Metal/ambient	35
Weldment/parent metal	4500

Table 4 : Heat transfer coefficients used in simulation

RESULTS & DISCUSSION

Welding can be considered as a casting process in which base metal plates act like a mold of infinite dimension. Since separation between fusion zone and base metal is not intended, a non-bonding at the interface in the form of air gap does not exist in the case of welding. Further, liquid pool in the case of welding is not stationary with respect to mold axis, unlike in the casting process where it is stationary. Therefore, the assumption of quasi-stationary condition is introduced in the present simulation model.

The thermal history at locations TC1 & TC2 is shown in Figure 2. The thermocouple data was used to predict the heat-affected zone (HAZ) width and also used as input to an inverse heat conduction model to determine the heat flux transients. The mathematical details of the inverse model are given in reference 10.

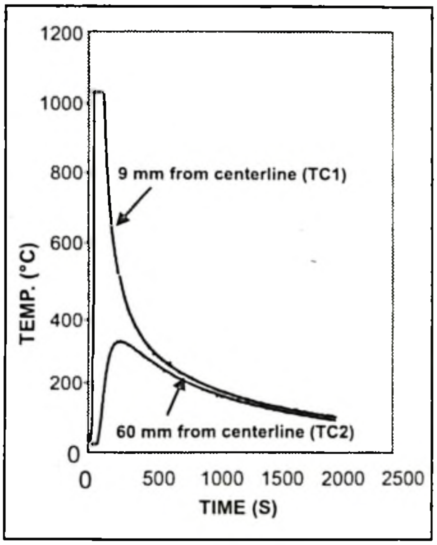

Figure 2 : Thermal history at thermocouple locations 1 & 2 during welding

HAZ is the area of base material where the temperature exceeds 723°C. In this region, microstructure and properties are altered. The peak heat flux was found to be 12.8 MW/m^2. The heat flux transients decreased sharply after the peak is reached. Figure 3 shows the thermal history of weldment at the liquid/base metal interface. The profile in the figure indicates that the liquid metal cooled rapidly from the maximum temperature in the groove. There is a change in slope in the curve due to the evolution of latent heat of fusion at its melting point. The drop of temperature along the transverse direction of base metal is due to the diffusion of heat through the base metal. Temperature profiles at various distances from the interface are shown in Figure 4 for a plate thickness of 5mm. The corresponding temperature profiles for a plate of 30mm thickness are shown in Figure 5. Due to high heat transfer coefficient at the initial stage a peak temperature of 1050°C was recorded. With increase in distance from weld centerline, the peak temperature started to decrease.

The peak temperatures attained at distances of 9mm, 20mm, and 30mm away from weld centerline

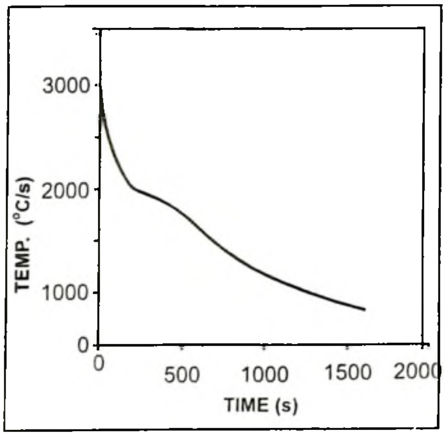

Figure 3 : Simulated thermal history of weldment

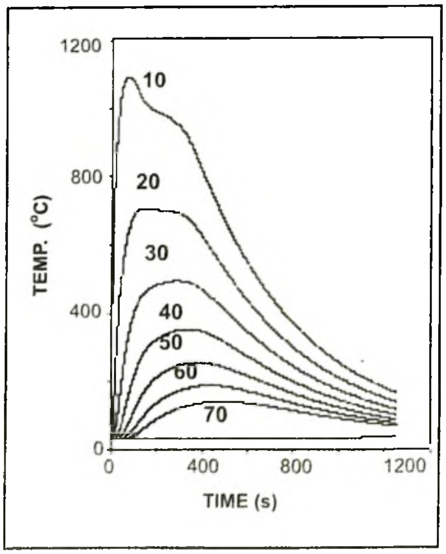

Figure 4 : Simulated temperatures at various distances in mm from the centerline ; Plate Thickness : 5mm

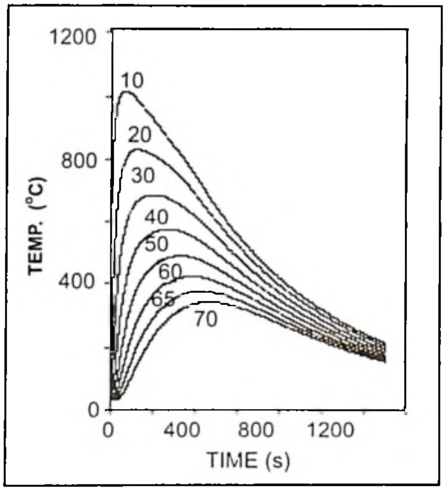

Figure 5 : Simulated temperatures at various distances in mm from the centerline; Plate Thickness: 30 mm

are 1050°C, 790°C, and 700°C respectively. The first curve stays approximately 40 s at the corresponding peak temperature and then decreases drastically. The second curve stays nearly 300 s at its peak temperature. Similarly third curve spent approximately 275 s but it is well below the lower critical temperature (Ac_1=723°C). The thermal status as indicated by third profile does not influence the microstructural changes, as it does not reach the austenitic region. The region corresponding to the first curve will not result in a coarse structure as it spends less time above 910°C. However, it should be noted that the cooling rate in this condition is quite large and this could bring about microstructural changes.

The region 20mm away from weld centerline was at its peak temperature (790°C) for a longer duration causing complete austenitizing of the material. But the probability of formation of martensite is less at this region since the cooling rate is considerably lower. The situation is quite contrary at a region 9 mm away from weld centerline. Here the region spends shorter duration of time (70 s) at its peak temperature (1050°C) causing incomplete austinitization. But faster cooling rate in this region may give rise to a small quantity of martensite precipitation. The simulation study suggests that the chances of formation of martensite are negligible at both the regions - 9 mm and 20 mm away from weld centerline. The study also indicates that there is a region away from weld centerline where austinitization is possible and with lower cooling rates, different microstructures (fine pearlite, coarse pearlite) may be obtained.

The profile of temperature distribution also indicates that there is a certain region around the fusion zone in which temperature has gone high enough (>Ac_1=723°C) to bring a change in microstructure when the region is cooled.

In order to predict changes taking place in the microstructure around the weld pool, cooling curves at various positions are superimposed on CCT diagram. If the cooling rate happens to be more than the critical cooling rate, precipitation of martensite is a complete possibility. If it is less than the critical cooling rate there is no possibility of precipitation of martensite. The simulation data indicates that in all the cases the cooling rate is happens to be less than the critical cooling rate indicating no possibility of precipitation of martensite. However a small amount of

AVAILABLE REGULARLY

FERRO-ALLOYS, NON-FERROUS METALS IN LUMPS/CHIPS/POWDER FORM
EX-STOOK IMPORTED / INDIGENOUS (WITH CENVAT BENEFITS)

- Ferro Boron
- Ferro Chrome ELC/LC/HC
- Ferro Columbium/Niobium
- Ferro Manganese ELC/LC/MC/HC (Low Phosphorous)
- Ferro Molybdenum
- Ferro Phosphorous - P 25%
- Ferro Silicon-Si 45-50%,70-75%
- Ferro Silico Calcium (Calcium Silicide)
- Ferro Silicon Zirconium
- Ferro Titanium-Ti 30-35%,40-45%
- Ferro Tungsten
- Ferro Vanadium
- Chromium Metal
- High Carbon Chromium Metal
- Cobalt Metal
- Silicon Metal 441 & 553 grade
- Manganese
- Nickel
- Iron Powder 40.29 & Cutting grade
- Iron Powder Electrolytic Grade
- Tungsten Metal Powder
- Tungsten Carbide
- Graphite Powder (Natural-Silver Grey)
- Fluorspar - Acid Grade & Metallurgical grade
- Potassium Titanate Powder

ISO-9001:2000 COMPANIES :

- *JAYESH TRADING CO.*
- *FERRO-CHEM INDUSTRIES*
- *EVER BRIGHT TUBE CORPORATION*
- *JAYESH INDUSTRIES LIMITED.*

JAYESH GROUP

605-9, Krushal Commercial Complex, Above Shoppers Stop, G. M. Road, Amar Mahal, Chembur (W), Mumbai - 400089. (INDIA) • Tel. : +91-22-6703 9991 / 4011 9991 / 2526 0983 • Fax : +91-22-6703 9990 / 2526 0986
TOLL FREE : 1800-22-9997 • E-mail : info@jayeshgroup.com / contact@jayeshgroup.com • Website : www.jayeshgroup.com

THE FIRST CHOICE

sharp

TURN-KEY PROJECT AND MACHINERY FOR MANUFACTURING MMAW ELECTRODES, MIG / CO_2 WELDING WIRE, TIG WELDING WIRES, SAW WIRES & SAW FLUX

SATISFIED CUSTOMERS IN 22 COUNTRIES

ENGINEERING EXCELLENCE sharp SINCE - 1967

ISO 9001 COMPANY

TÜV SÜD Management Service

SHARP TOOLS

Kalappatti, Coimbatore - 641035, India
Phone: +91 422-2628131, 2628132 Fax: +91 422-2627631
E-mail:since1967@sharptools.com Web:www.sharptools.com

martensite can be dispersed as the cooling curve at 9mm away from weld centerline does not fall completely in the pearlitic region.

EFFECT OF PREHEAT AND PLATE THICKNESS

Preheating the metal influences conditions of heat transfer away from liquid metal. The temperature profiles indicated that as the preheating temperature increases the rate of cooling decreases. Figure 7 shows the effect of preheat temperature on cooling rate.

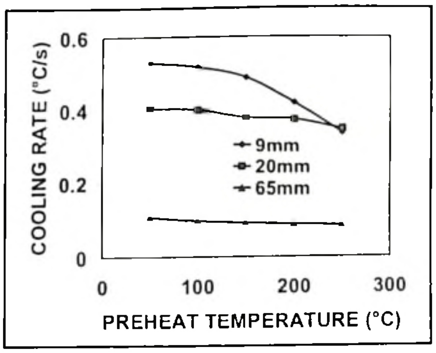

Figure 7 : Effect of preheat temperature on cooling rate at various locations

The cooling rate decreases with increase in temperature. Preheating of the base plate is beneficial because lower cooling rate in any region of base metal implies less probability of martensitic transformation. The initial temperature plays an important role in the temperature distribution and heat cycle associated with welding. The soaking time increases and the cooling rate decreases with initial higher temperature of the base plate

Welding of complex shape jobs involve joining plates of different thicknesses. Variation of the thickness is an important parameter in a welding process. The effect of plate thickness on cooling rate is shown in Figure 8. It shows that as the thickness of the plate increases, the cooling rate also increases. The thickness of the plate influences maximum peak temperature attained during welding. Maximum peak temperature attained in a thin plate (5mm) was 1050°C and corresponding cooling rate is 4°C/s.

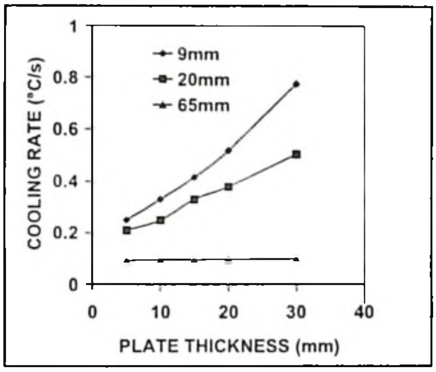

Figure 8 : Effect of plate thickness on cooling rate at various distances

On the other hand, in the case of thick plate (30 mm) the peak temperature is lower. But it shows a cooling rate of 16°C/s above 723°C. This indicates that as the plate thickness increases cooling rate also increases, but the peak temperature decreases for a given heat input.

VALIDATION OF SIMULATION RESULTS

The parent metal thermal history (Figure 2) derived from experimental measurements shows that as soon as the welding is over the location near to the interface is heated rapidly to a maximum temperature. This temperature either remains constant for small period or drops down depending on the parent metal thickness and preheating temperature.

The first curve shows the temperature distribution of weld structure as recorded by the thermocouple located 9 mm away from weld centerline and second curve shows the corresponding reading at 60 mm away from weld centerline. The first curve indicates the decrease of temperature after 91 seconds. This period corresponds to the beginning of cooling of parent metal. After the complete solidification of weldment the temperature at the interface drops down as heat conduction inside the parent metal becomes more predominant than heat dissipation in the weldment. The second curve, which corresponds to the location 60 mm away from weld centerline, shows a maximum temperature of 360°C and drops with a moderate cooling rate. From the figure it is observed that the cooling rate at 9 mm away from weld centerline is greater than the cooling rate at 60 mm away from weld centerline. The soaking time at 275°C for 9 mm away from center line is 651 s and that for 60 mm away from weld center line is 431 s.

During the very beginning stage of cooling, both simulated and experimental curves show identical cooling rate. However, at the later stages there is a deviation from the experimental data. A temperature of 400°C is attained in approximately in 500s. But, the simulation results show that about 900s is required to reach 400°C. The experimental data related to the later stages show a slow cooling rate but this is not observed in the case of simulation. But overall cooling rate is nearly same as that of simulated data. This is because in simulation the weldment is considered as a single medium and the initial temperature is assigned at the beginning of the simulation.

During simulation heat transfer from weldment to base metal starts from entire weldment portion. But this is not true in the case of actual welding. Welding starts from one end and progress towards the other. The moment welding starts, a transient condition arises and subsequent cooling rate will be generally high. As welding proceeds it changes from transient to quasi-stationary state and as a result, the cooling rate starts to decrease. In contrast, during simulation, the quasi stationary condition is considered during the whole run.

Figure 9 : Microstructure of base metal after welding.

The peak temperature at this zone of base metal rises up to about 550°C. The microstructure shows pearlitic ferrite structure similar to that generally found in a plate prior to welding. Figure 10 shows the microstructure of heat affected zone.

Figure 10 : Microstructure of the Heat Affected Zone (HAZ)

Due to grain growth the austenite decomposition is slower and this favors ferritic precipitation in the plane of austenite with formation of Widmanstatten structure.

Figure 11 : Microstructure of the weld metal

Weld metal structure is essentially a cast structure. It shows a dendritic structure. At the interface Widmanstatten structure was observed. The structure that forms at weldment region depends upon the temperature gradient, G and solidification rate, R. If G/R ratio is more a planar structure is obtained. On the other hand, if the ratio is less a dendritic structure will be observed. In the weldment region the temperature gradient will be very less and solidification rate is high. A dendritic microstructure is observed in the weldment region due to extensive constitutional undercooling.

LIMITATIONS OF THE PRESENT SIMULATION

Heat transfer coefficients used in the present simulation are found out by a trial and error method. The simulation work can be improved by determining the actual heat transfer coefficients. The liquid pool is considered as a single stationary source but in real welding, the liquid pool is not stationary but moves from one end to other. The heat transfer may be different in two cases. It was further assumed that the welding speed is uniform. This assumption may not be true, particularly in manual welding.

CONCLUSIONS

The peak temperature, time duration spent by the material above the critical temperature and cooling rate along the length of the base meta are predicted using heat flow simulation. Predicted peak temperature and cooling rate fairly agree with those obtained from the experimental measurements. Superimposing of experimentally measured cooling curves on CCT diagram of rail steel revealed that martensitic transformation has not occurred. The absence of martensite is practically verified by metallographic study. The cooling rate and peak temperature are influenced by parameters like preheating temperature and plate thickness. Using simulation study, it is possible to suggest the preheating temperature for the welding of plates of given thickness in order to eliminate the precipitation of deleterious type of martensite in HAZ region.

REFERENCES

1. ASM Hand Book, vol.6 Welding brazing and Soldering, ASM International, OH, pp. 1-97
2. Fajita, J Kinngawa, A Okada and J. Kasagai, Prediction of the properties of weld heat affected zone, Data Science Journal 2 (2005) 136
3. M.A.Wahab, M.J.Painter and M.H.Davies, Prediction of temperature distribution and weld pool geometry in the gas metal arc welding process, Journal of Material

Processing Technology 77 (1998) pp. 233-239

4. C.H.Kim,W.Zhang and T.Debroy, Modelling of temperature field and solidified surface profile during gas metal arc fillet welding, Journal of applied physics, 94 (2003) pp. 2667-2679
5. Y.W. Chan, Computer simulation of heat flow in pulsed current arc welding, Journal of Materials Processing Technology, 38 (1993) pp.449-463
6. M. Hang, Computation of GMAW welding heat transfer with boundary element method, Advances in Engineering Software, 16 (1993) pp. 1-5
7. D. Deng and H. Murakawa, Numerical simulation of temperature field and residual stress in multi-pass welds in stainless steel pipe and comparison with experimental measurements, Computational Materials Science, 37 (2006) pp.269-277
8. F. Shehata, Effect of plate thickness on mechanical properties of steel arc welded joints, Materials and Design, 15 (1994) pp. 105-110
9. SolidCast User Manual, Finite Solutions Inc., OH, USA

K. N. Prabhu and A. A. Ashish, Inverse Modelling of Heat Transfer with application to Solidification and Quenching, Journal of Materials and Manufacturing Processes, 17 (2002) pp. 469481

Guidelines for acceptance & publication of Technical Papers in the Indian Welding Journal

TYPES OF CONTRIBUTION

Original Papers

Dealing with research, technology & industrial applications. should be typically around 3500 words, plus figures & tables. Authors are requested to give an understanding that the matter is original.

Conference Papers

Materials submitted to conferences may be accepted, particularly if it is expanded or modified and provided that the Editor considers that the paper would be of interest to the wider readership of the Indian Welding Journal. The authors are responsible for obtaining the consent of the editor / sponsor of the conference proceedings to publish the materials in the IWJ.

Critical assessment/Reviews

dealing with a welding or joining subject ina critical, comprehensive and well referenced manner. typically around 3500 - 4000 words plus figures & table. The reference of the conclusions of the research work or the review to industrial practice should be emphasized.

SUBMISSION OF THE PAPERS

All papers should be sent to the Editor at the Head Quarter of the Indian Institute of Welding. Normally an acknowledgement of receipt will be sent within one week by E-mail. Papers should be printed in 3 columns (Please refer January / April 2005 issue of the IWJ) and sent in a CD over & above the hard print. Figures, Diagrams & sketches should be neat and clearly legible. All the papers after preliminary screening by the Editor will be sent to one or more of Review Panel Members (see list below).

Based on the feedback, the Editor will decide about publication subject to space availability in a particular issue. A final communication about acceptance / modification / non-acceptance of the papers would then be sent to the authors in due course. Normally, the authors expecting their papers to be published in a particular issue should send the manuscript at least 2 months before the issue date.

REVIEW PANEL MEMBERS

Prof. G. L. Datta, Prof. S. Sundaresan, Prof. T. K. Pal, Prof. P. K. Ghosh, Mr. R. Banerjee, Mr. R. Ravi, & Mr. A. K. Bhaduri.

Note : Authors willing to publish their papers in the October 2007 issue are requested to send the same immediately as per above norms.