1. INTRODUCTION

Low carbon steel of SA 516 GR 70 is being widely used as a major structural material for boiler plates in view of its good high temperature mechanical properties and adequate weld ability [1]. These steels owing to their excellent high temperature mechanical properties, find wide applications as piping and super heater tube material in steam generating plants [2].

The duplex microstructure consisting of ferrite and pearlite phases transforms to carbides and brittle intermetallic phases [3]. Consequently, the creep properties of the weld metal would be significantly influenced by the kinetics as well as the nature of the products of this transformation which in turn strongly depend on the chemical composition of the deposit [4]. This investigation is aimed at understanding the characterization, mechanical properties like micro hardness and creep behavior of SA 516 GR 70 alloy shielded metal arc welds.

Impression creep technique is a modified indentation creep test wherein the conical or ball indenter is replaced by a cylindrical, flat bottomed punch [5]. The usefulness of this technique, pioneered by Prof. Li, is illustrated by application to a variety of problems [6]. High temperature creep behavior of a number of metals and alloys, particularly estimation of the thermal activation parameters aiding the identification of the rate controlling mechanisms of creep, has been investigated.

This test offers several advantages over the conventional creep testing. It is the most suitable method to study the creep behavior of welded portion; a small process zones HAZ [7]. It takes the shorter duration for test, and small quantity of the testing material. The temperature and stress dependency of creep rate could be obtained on a single sample. The test can be carried out with a constant stress at constant load. Utilizing the impression creep test, the creep behavior of individual zones in steel weldment has been examined. Experiments have been carried out to investigate the indentation (impression) creep on SMAW welded SA 516 GR 70. Samples were selected from the plates which had been SMAW. Impression creep behavior of samples was studied using tungsten carbide indenter at various stress levels and various temperatures. From the creep profiles steady state creep rates (\(\dot{\varepsilon}\)) were calculated. Further stress exponent and activation energy values were also determined. Creep rates for three regions are compared.
2. MATERIAL AND EXPERIMENTAL DETAILS

2.1 Material Composition

The SA 516 GR 70 steel plates are used in this investigation to produce the weldment’s in five different layers. The specifications of the plate of SA 516 GR 70 are 325 mm x 293 mm x 12 mm and the nominal chemical specification of SA 516 GR 70 steel plate is; C: 0.27%, Mg: 0.79-1.30%, Ph: 0.035%, S: 0.035% and Si-0.20-0.4%.

2.2 Shielded Metal Arc welding unit

Welded joints of SA 516 GR 70 with a thickness of 12 mm. Butt type of joint were prepared by using SMAW technique (Fig.1). The welding parameters are shown in Table 1.

![Fig. 1. Schematic drawing of Shielded Metal Arc Welding Unit](image)

2.4 Length of HAZ for Welded Plate

The weld samples contain three zones i.e. parent material (PM), heat affected zone (HAZ) and fusion zone (FZ). But, visual observation is not sufficient to predict the actual length of HAZ. So, length of HAZ is calculated through theoretical correlations and shown in Table 2 for all the conditions.

\[
H_{net} = \frac{\eta \cdot E \cdot I}{V}
\]

\[
\frac{1}{T_p - T_o} = \frac{4.13 \cdot \rho \cdot p \cdot V}{N_{net} + \frac{1}{T_m - T_o}}
\]

2.5 Sample Preparation

Samples for various tests were taken from parent metal (PM), heat affected zone (HAZ) and fusion zone of welded steels. Specimen of size 35mm x 12 mm were cut from the welded steels as presented in the schematic diagram presented in Figure 2.

![Fig. 2. Schematic diagrams for the cutting plane of the welded sample](image)

<table>
<thead>
<tr>
<th>Run</th>
<th>Process</th>
<th>Size of Filler Metal (A)</th>
<th>Voltage (V)</th>
<th>Type of current Polarity</th>
<th>Wire feed speed (mm/min)</th>
<th>Heat input (KJ/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAYER 1</td>
<td>SMAW</td>
<td>2.50</td>
<td>22-24</td>
<td>DCEP</td>
<td>90</td>
<td>1.01</td>
</tr>
<tr>
<td>LAYER 2</td>
<td>SMAW</td>
<td>3.15</td>
<td>18-20</td>
<td>DCEP</td>
<td>196</td>
<td>1.01</td>
</tr>
<tr>
<td>LAYER 3</td>
<td>SMAW</td>
<td>4.00</td>
<td>16-19</td>
<td>DCEP</td>
<td>205</td>
<td>0.76</td>
</tr>
<tr>
<td>LAYER 4</td>
<td>SMAW</td>
<td>3.15</td>
<td>20-22</td>
<td>DCEP</td>
<td>190</td>
<td>0.91</td>
</tr>
<tr>
<td>LAYER 5</td>
<td>SMAW</td>
<td>3.15</td>
<td>20-24</td>
<td>DCEP</td>
<td>195</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Table 1. Experimental conditions for SMAW process

<table>
<thead>
<tr>
<th>Layer</th>
<th>Wire feed speed (mm/sec)</th>
<th>Heat input (KJ/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>1.38</td>
<td>2.67</td>
</tr>
<tr>
<td>Layer 2</td>
<td>3.27</td>
<td>1.58</td>
</tr>
<tr>
<td>Layer 3</td>
<td>3.41</td>
<td>1.91</td>
</tr>
<tr>
<td>Layer 4</td>
<td>3.17</td>
<td>2.19</td>
</tr>
<tr>
<td>Layer 5</td>
<td>3.25</td>
<td>2.04</td>
</tr>
<tr>
<td>Layer 6</td>
<td>3.27</td>
<td>2.20</td>
</tr>
</tbody>
</table>

Table 2. Length of HAZ for different layers

2.6 Micro-structural Studies

The cut samples are polished using surface grinding machine and then mechanically ground polished using 1/0, 2/0, 3/0, 4/0 grade papers. Next these samples are polished on a disc polishing machine by using diamond paste as abrasive medium until a flat and scratch-free mirror-like finish was obtained. To reveal the micro-structure, the sections were etched in 3% nital solution, rinsed in deionized water, and dried with drier.
2.6.1 Optical metallographic
Polished Samples were taken for microscopic examination and photomicrographs were taken with the help of standard metallurgical optical microscope and digital image recorder at appropriate magnification.

2.6.2 Scanning electron microscopy (SEM)
Micro structures of the polished sample were studied using SEM on the PM, HAZ and FZ. Secondary electron images were recorded with appropriate magnification.

2.7 Micro hardness
Micro hardness measurements were made on welded specimens using Knoop micro hardness equipment. Measurements were taken for each condition at five different lengths along the weld with a load of 100 kgf.

2.8 Impression creep studies
Specimen cut from the different zones are grounded parallel using cylindrical grinding machine and etched to reveal the various zones. Photograph of such a specimen is presented in Figure 3.

![Fig. 4. The schematic line diagram of the impression creep setup (A1- Furnace, A2- Specimen cage, F - Pull rod, G - LVDT transducer, H- Spirit level, I- I beam frame, K- Balancing weight, L - Lever arm, W - Weight, TC - Thermocouple, FL - Furnace leads)](image)

![Fig. 5. Specimen cage setup (F- Full Rod, C- Indenter, B-Specimen)](image)

![Fig. 6. Dimensions of the tungsten carbide indenter (\(d = 2 \text{ mm } h = 1.967 \text{ mm } h_1 = 1.127 \text{ mm}\), Area of the base is 3.1416 mm\(^2\)])(image)

2.8.1 Impression creep testing apparatus
The schematic line diagram of the creep machine set up used in the present study is shown in Figure 4. In this machine compression load is applied to the sample by means of a cage set up as shown in Figure 5. The cage consists of two rectangular components R\(_1\) and R\(_2\). R\(_1\) is fixed to the base plate and R\(_2\) to the pull rod which is connected to the lever arm. When load is applied R\(_1\) will remain stationary, R\(_2\) will move up. As a result, the indenter fixed to the top plate of R\(_1\)will remains stationary whereas the bottom plate of R\(_2\) containing the specimen will be pulled up which results in the impression of the indenter on the specimen.

Since the experimental work is at both room temperature and high temperature, the specimen cage must be made from a material capable of withstanding high temperature and must undergo zero deformation at the testing temperature throughout the testing period. The material which meets requirement of a specimen cage is Nimonic 90 (Methane grade super Ni 90) cold rolled and annealed 14 mm rods procured from Mishra Dhatu Nigam Limited, Hyderabad.
The pull rod connected to the cage is also connected to the lever arm (L). These two parts of the pull rod are held together by a stainless steel block. The precise alignment of the pull rod and the specimen cage is very important to obtain good results. A platform is attached to the upper pull rod which presses against the transducer and measures the displacement. A horizontal 25mm thick steel plate is supported by means of two vertical channels. A 12.5mm thick stainless steel plate is supported from the above steel plate by means of four steel rods. The specimen cage is fixed to the stainless steel plate. A furnace also rests over it for high temperature creep testing. The dimensions of the tungsten carbide indenter used in the present work are shown in Figure 6.

Fig. 7. Impression creep setup used in the present work

2.8.2 Impression creep testing

The specimens, prepared as mentioned above, were polished by standard metallographic techniques and were tested for parallelism of faces before introducing into the specimen cage of the machine. The specimen (B) kept in one part of the super alloy cage (A2) as shown in Figure 3 and the other part of the cage contains the cylindrical indenter (C) of diameter 2 mm made of tungsten carbide (its axis coinciding with the axis of the pull rod). Using the balancing weight (K) and the spirit level (H) the lever was initially kept horizontal. Now the specimen was made to touch the indenter. The load was applied gradually at the other end of the lever which was dipped in machine oil in order to avoid damping.

The indenter displacement could be measured with an accuracy of 1 micron. The readings are noted for every 1 minute until the steady state was reached. The creep testing was done on three zones of specimen with different loads and different temperatures.

3. RESULTS AND DISCUSSIONS

Figures 8 and 9 shows the banded structure of ferrite (white region) and pearlite (black region). This chapter includes results obtained from optical microscope, SEM on unpeened and laser peened samples. Microhardness and creep test results are tabulated and plotted.

3.1 Microstructures

Micro-structural features of SA 516 GR 70 grade steels in Parent, Heat affected and Fusion regions of the welds are recorded using optical and scanning electron microscopes and presented in Figures 8a to 8c and 9a to 9c.

Fig. 8. Optical photomicrograph. a) PM (SA 516 GR 70); b) FZ (SA 516 GR 70), etchant Nital 3 %; c) HAZ (SA 516 GR 70), etchant Nital 3 %;

Fig. 9. Microstructures of SA 516 GR 70: a) PM; b) FZ; c) HAZ

Following observations can be made on Photomicrographs:
(i) Parent metal consists of banded ferritic and pearlitic structure. Pearlite content is around 30 %.
(ii) Fusion zone consists of very fine ferrite and pearlite, well distributed throughout, banded structure disappears.
(iii) Heat affected zone consists of fine ferrite and pearlite. Ferrite is seen surrounding the pearlitic region as in the case of steel containing more than 0.45 % Carbon.
(iv) Martensitic or bainitic are not observed in HAZ zone.

3.2 Micro hardness results for welded material

Hardness results of individual zones of steel material are given in Table 3. Hardness profile over the weldment steel material is presented in Figure 10.
### Zones Hardness (HV)

<table>
<thead>
<tr>
<th>Zones</th>
<th>Hardness (HV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent Metal</td>
<td>165</td>
</tr>
<tr>
<td>Heat Affected Zone</td>
<td>183</td>
</tr>
<tr>
<td>Fusion Zone</td>
<td>188</td>
</tr>
</tbody>
</table>

Table 3. Micro hardness results for unpeened and peened welded material

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Parent metal is supposed to show a constant hardness. The area where hardness is changing may be regarded as HAZ.

Following points are revealed by the values presented in Table 3 and Hardness profile in Figure 9c:

(i) Fusion zone records highest hardness, followed by heat affected zone and parent metal.

(ii) Contrary to expectation highest hardness is not recorded by HAZ.

(iii) Hardness varies from 165 – 187 VHN in welded material.

### 3.3 Steady state creep test results

Steady state creep test was performed at 10 kg and 12 kg loads for different temperatures and for different zones. The results of the test are tabulated in Table 4.

Creep rate measurement over the weldment successful. Following observations can be made on the Table 4.

(i) Fusion zone records the lowest steady state creep rate, followed by heat affected zone and parent metal under all the conditions of load and temperatures of testing.

### 3.3.1 Activation energy

Activation energy was calculated at 10 kg and 12 kg loads for different temperatures and for PM, HAZ, FZ regions. The results of the test are tabulated in Table 5.

For all the zones, Activation energy increases as the temperature increases. Activation energy is in the range of 20 – 46 for 10 kg load, and 15 – 41 for 12 kg load.

### 3.3.2 Stress exponent values

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Fusion Zone</th>
<th>Heat Affected Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT</td>
<td>4.38</td>
<td>5.67</td>
</tr>
<tr>
<td>100</td>
<td>7.33</td>
<td>6.05</td>
</tr>
<tr>
<td>200</td>
<td>3.40</td>
<td>5.14</td>
</tr>
</tbody>
</table>

Table 6. Stress exponent values

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4. RESULTS AND DISCUSSIONS

Welding is the joining process involving high thermal input. The thermal effect creates distinctly three microstructural zones, viz: fusion zone (FZ), heat affected zone (HAZ) and parent metal (PM). The spread of the fusion and heat affected zone depends on the process of welding. With the present process of
shielded metal arc welding (SMAW) the width of fusion zone is around 6 mm. Heat transfer equation is used to find out the thickness HAZ and it is found that it extends by 2-3 mm. The calculation of thickness of heat affected zone is given in the appendix. Impression creep testing is one of the convenient methods for mechanical characterization of the micro regions like fusion zone and heat affected zones, at room temperature and higher temperature. Further, values of steady state creep rates can be used to find out the activation energy ($Q^*$) which reveals the mechanism of creep.

The laser treatment on the surface of the weldment is expected to induce the residual compressive stresses and its mechanical properties, including creep. Further, three regions with different micro-structural features are expected to respond differently to the laser treatment. Hence, laser beam of power 50 mJ is scanned over the welded plates in single and double rows. However, it is found that surface of weldment got damage due to the action of laser. The initiation of cracks in the laser affected area is clear from the SEM photomicrograph presented in figures 8a to 9c.

4.1 Details of microstructure

Following are the observations for sample:

(i) Parent metal consists of banded ferritic and pearlitic structure. Pearlite content is around 30 %. As the base metal was cold rolled, banded ferritic and micro-structural characteristics of three zones have been investigated by optical microscope and scanning electron microscopy (SEM) for samples pearlitic structure was found.
(ii) Fusion zone consists of very fine ferrite and pearlite, well distributed throughout. Banded structure disappears as it reaches austeniting temperature.
(iii) Heat affected zone consists of fine ferrite and pearlite. Ferrite is seen surrounding the pearlitic region as in the case of steel containing more than 0.45 % Carbon.
(iv) For low carbon steels, the nose in the TTT diagram will be nearer to the y axis. As the percentage of carbon increases, nose pushes to the right of the TTT diagram. As the distance of nose from y axis increases, there is a chance of formation of martensite or bainite. So, martensitic or bainitic are not observed in HAZ zone the hardness value is in the range of 165 – 188 VHN.

5. CONCLUSIONS

Based on the present investigation following conclusions have been arrived at. The activation energy in the range of 15 – 46 kJ/mol and stress exponent values in the range of 3.4 – 7.33 suggest that the dominant mechanism is dislocation creep. Hardness value is more in Fusion zone compare to Parent and Heat Affected zones.

REFERENCES


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