Tensile and Fracture Properties of Circumferentially Notched Tensile Specimens of Stainless Steel Weldments

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ABSTRACT

The tensile and fracture properties of different types of austenitic stainless steel weldments were determined using round notched tensile specimens. These included 304L, 316L and 6%Mo super austenitic stainless steels and their weld metals. The triaxial state of stress, the plastic constraint and the plane strain conditions developed ahead of the notch root make notched specimens eligible for the evaluation of fracture toughness. This was achieved through the testing procedure: J-evaluation on tensile test (JETT) using circumferentially notched round bar specimens. The JETT index was taken as a measure of the relevant elastic-plastic fracture toughness of the tested materials. In the case of austenitic stainless steels being too ductile at room temperature the resulted JETT were of relatively higher values than the fracture toughness values determined from the standard fracture mechanics test methods. This could be related to the difference in the stress state ahead of the sharp crack of the standard fracture mechanics specimen and that of the blunt notch of the tensile specimen. The results showed that the 6% Mo weld metal ranked highest while the 316L weld metal ranked lowest regarding JETT fracture toughness values. The deformation mechanisms pertinent to austenitic stainless steels (generation of stacking faults and formation of strain induced martensite) were employed for the interpretation of the experimental results.

Key words: Austenitic stainless steels weldments, Round notched tensile specimens, Elastic-plastic fracture toughness.

INTRODUCTION

Austenitic stainless steels find wide applications as structural materials and components of heat transfer equipment in the chemical, petrochemical, and conventional industries. Main parts of nuclear power industries are also manufactured of austenitic stainless steels such as cladding materials of pressure vessels and control rod assemblies. They also constitute integral parts of the components of both the front end and back end of the nuclear fuel cycle [1]. The corrosion resistance of these materials has been greatly enhanced through the development of low carbon Mo free 304L alloy and Mo bearing steels (316L). The latest development in this category of alloys involves the SMO-254 alloy, which contains a higher Mo content (6%), 17% Ni and minor amounts of N and these alloys were classified as super austenitic stainless steels [2].

The tensile and fracture properties of austenitic stainless steels are of much concern since they determine to a great extent the aptitude of these materials to verify the in-service safety requirements. These properties are determined by their relevant microstructure which is a function of their chemical composition and the applied heat treatment. Austenitic stainless steels being of face-centered cubic crystal structure are mostly too ductile at room temperature. Accordingly, their tensile and fracture behaviour is mainly related to ductile deformation and fracture mechanisms [3].

Design of structural components is based on fracture toughness which is considered one of the most important mechanical properties for structural integrity assessment. If a material undergoes ductile fracture it will have high level of fracture toughness (elastic-plastic fracture). The
Fracture toughness is obtained by using laboratory size specimens that meet certain requirements and is usually measured by tests based on appropriate fracture mechanics theories [4, 5]. Unfortunately, fracture mechanics tests are complex and expensive to conduct. In addition, fatigue pre-cracking of the specimens is required in order to obtain sharp crack to determine the elastic-plastic fracture toughness ($J_{IC}$). On the other hand, a convenient new test method, named J-evaluation on tensile test (JETT) of round bar with circumferential notch, has been proposed to evaluate the fracture toughness of tough materials [6]. The triaxial state of stress, the plastic constraint and the plane strain conditions developed ahead of the notch root make notched tensile specimens eligible for the evaluation of fracture toughness. Since the fracture energy expended during the tensile test has the same units of these which describe the elastic-plastic fracture toughness determined by the standard fracture mechanics test (kJ/m$^2$), the JETT index can be used as a measure of the elastic-plastic fracture toughness. In this study, the tensile testing of round notched tensile specimens was utilized to compare the elastic-plastic fracture toughness of the tested materials as expressed by the JETT index.

**EXPERIMENTAL**

The base metals of the materials used in this investigation were the conventional 304L, 316L stainless steels and the 6% Mo super austenitic stainless steel and their corresponding weld metals. The chemical composition of these alloys is given in Table 1.

The base metals of the 304L, the 316L and 6% Mo steels were received in the solution heat treatment condition. The solution heat treatment was conducted at 1120 °C followed by water quenching. Gas shielded arc welding (GSAW) was applied using the filler material electrodes shown in Table 1.

Test specimens were in the form of notched tensile round bars with a diameter of 8 mm, 4mm notch diameter, 30 mm gauge length and a total length of 150 mm. The notch angle was 60° and the root radius was 0.75 mm. The tensile properties were evaluated at room temperature using Zwick standard electromechanical testing machine at a strain rate of 5x10$^{-4}$s$^{-1}$. These included: stress–strain curves, yield strength ($\sigma_y$), ultimate tensile strength ($\sigma_u$), strain hardening exponent (n) and the reduction in area (RA%). Fracture surface morphology of the tested materials in the base metal and weld metal conditions was examined using scanning electron microscope (SEM), Jeol-JSM-400.

**Table 1: Chemical composition of base metals**

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>304L BM</td>
<td>0.020</td>
<td>0.42</td>
<td>0.87</td>
<td>0.022</td>
<td>0.007</td>
<td>17.02</td>
<td>8.10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>304L WM</td>
<td>0.030</td>
<td>0.40</td>
<td>1.50</td>
<td>0.023</td>
<td>0.006</td>
<td>18.40</td>
<td>10.43</td>
<td>0.27</td>
<td>0.03</td>
</tr>
<tr>
<td>316 L BM</td>
<td>0.021</td>
<td>0.52</td>
<td>0.85</td>
<td>0.026</td>
<td>0.005</td>
<td>17.59</td>
<td>11.50</td>
<td>2.28</td>
<td>0.06</td>
</tr>
<tr>
<td>316 LWM</td>
<td>0.080</td>
<td>0.41</td>
<td>1.60</td>
<td>0.025</td>
<td>0.003</td>
<td>19.07</td>
<td>11.70</td>
<td>2.30</td>
<td>0.02</td>
</tr>
<tr>
<td>6%Mo BM</td>
<td>0.013</td>
<td>0.50</td>
<td>0.60</td>
<td>0.020</td>
<td>0.003</td>
<td>19.30</td>
<td>17.80</td>
<td>6.10</td>
<td>0.22</td>
</tr>
<tr>
<td>6%Mo WM</td>
<td>0.02</td>
<td>0.30</td>
<td>0.70</td>
<td>0.022</td>
<td>0.003</td>
<td>25.00</td>
<td>Bal.</td>
<td>15.0</td>
<td>-</td>
</tr>
</tbody>
</table>

B.M: Base metal, WM: Weld metal filler material electrode

**RESULTS**

**1. Tensile Properties:**

Figure 1 shows typical stress-strain curves of the tested materials. The main observation is that the 304L, the 316L and 6%Mo base metal steels display higher tensile strain ranges over that of their corresponding weld materials. On the other hand, the weld materials show superior tensile stress ranges over that of their corresponding base materials.
(a) 304L Base Metal
(b) 304L Weld Metal
(C) 316L Base Metal
(d) 316L Weld Metal
(e) 6%Mo Base Metal
(f) 6%Mo Weld Metal

Figure (1): Stress-Strain curves of the investigated materials
The tensile properties of the investigated materials after testing at room temperature are summarized in Table 2. Table 2 shows that the 6% Mo weld metal and 304L base metal have the highest (700, 950 MPa) and the lowest (460, 700MPa) yield and tensile strength, respectively. The 304L base metal displays the highest strain hardening capacity ($\sigma_y/\sigma_u$=0.66) while the 316L weld metal has the lowest value ($\sigma_y/\sigma_u$=0.87). The strain hardening exponent value as evaluated by uniform strain (strain at maximum load) was also highest for 304L base metal (n=0.35) and lowest for 316L weld metal (n=0.18). As regards the reduction in area, the highest value was for the 6%Mo base metal (RA%=75%) while the lowest one was for the 316L weld metal (RA%=30%).

Table 2: Tensile properties of tested alloys

<table>
<thead>
<tr>
<th>Material</th>
<th>$\sigma_y$, MPa</th>
<th>$\sigma_u$, MPa</th>
<th>$\sigma_y/\sigma_u$</th>
<th>n</th>
<th>RA %</th>
</tr>
</thead>
<tbody>
<tr>
<td>304L BM</td>
<td>460</td>
<td>700</td>
<td>0.66</td>
<td>0.35</td>
<td>65 %</td>
</tr>
<tr>
<td>304L WM</td>
<td>580</td>
<td>740</td>
<td>0.78</td>
<td>0.22</td>
<td>35 %</td>
</tr>
<tr>
<td>316L BM</td>
<td>600</td>
<td>750</td>
<td>0.79</td>
<td>0.20</td>
<td>55 %</td>
</tr>
<tr>
<td>316L WM</td>
<td>680</td>
<td>780</td>
<td>0.87</td>
<td>0.18</td>
<td>30 %</td>
</tr>
<tr>
<td>6% Mo BM</td>
<td>620</td>
<td>900</td>
<td>0.69</td>
<td>0.33</td>
<td>75 %</td>
</tr>
<tr>
<td>6% Mo WM</td>
<td>700</td>
<td>950</td>
<td>0.74</td>
<td>0.32</td>
<td>40 %</td>
</tr>
</tbody>
</table>

$\sigma_y$: yield strength, $\sigma_u$: tensile strength, $\sigma_y/\sigma_u$: strain hardening capacity n: strain hardening exponent and RA %: reduction in area.

2. Estimation of Elastic-Plastic Fracture Toughness:

The tensile test results were utilized to estimate the elastic-plastic fracture toughness ($J_{IC}$) of each material. This was performed by computing the area under the load-displacement curve for each material up to the fracture load which expresses the failure energy absorption. Dividing the values of the failure energy absorption by the original notched cross-sectional area produces JETT for each material. Since JETT has the same units of the elastic-plastic fracture toughness (kJ/m$^2$), it can be used as an estimate of $J_{IC}$. The values of JETT are presented in Table 3. As can be seen the JETT values of the investigated materials appear to be relatively higher than the values produced from standard fracture mechanics tests. This can be a result of the difference in the specimen size and consequently the stress state between the standard compact tension specimen and the notched tensile specimen. In the case of the compact tension specimen, which is of larger cross section the stress state is mainly of plane strain which tends to lessen the degree of ductile fracture. Decreasing the specimen size as in the notched tensile specimen increases the percentage of the specimen cross section which is under plane stress, a condition which promotes ductile fracture by minimizing constraint.

Table 3: JETT of the investigated materials

<table>
<thead>
<tr>
<th>Material</th>
<th>304L BM</th>
<th>304L WM</th>
<th>316L BM</th>
<th>316L WM</th>
<th>6% Mo BM</th>
<th>6% Mo WM</th>
</tr>
</thead>
<tbody>
<tr>
<td>JETT (kJ/m$^2$)</td>
<td>850</td>
<td>550</td>
<td>600</td>
<td>480</td>
<td>920</td>
<td>1050</td>
</tr>
</tbody>
</table>

3. Fractography:

Examination of the fracture surface of the tested specimens at low magnification demonstrated ductile fracture features characterized by fibrous morphology Fig. 2. This was identified at higher magnification as coalesced microvoids (dimples). The dimple size was finer in the case of the weld specimens of the 304L, 316L and 6% Mo alloy. This agrees with the tensile test results since the weld specimens exhibited higher strength and lower reduction in area levels than the base metal conditions (Table 2). As can be seen, the fracture surface of the 316L weld metal exhibits what can be identified
as cleavage facets (faceted regions). This can be associated with the high percentage of ferrite in its microstructure (10% ferrite).

**DISCUSSION**

The results showed that all the base and weld metal tested materials failed in a complete ductile manner. Fractographic morphology did not reveal any features of brittle fracture; no transgranular cleavage or quasicleavage aspects were identified except for the 316L weld metal which comprised some cleavage facets Fig. 2d. The difference in the tensile properties and fracture toughness (indicated by the JETT index) of the studied materials will be discussed in terms of the relation between alloy composition and deformation modes.

1 Deformation behaviour of 304L, 316L and 6%Mo stainless steels and their weld metals:

The chemical composition of the examined 304L, 316L and 6%Mo steels and their weld metals (Table1) shows that these materials are classified as austenitic stainless steels, i.e. having the austenite phase as the predominant microstructure.

Deformation of austenitic steels, such as during tensile testing, takes place either through formation of strain induced martensite or through generation of stacking faults in the face centered cubic structure of the austenite phase [7]. In order to check the possibility of the formation of strain induced martensite, the following equation [8] was employed. This equation is used to determines the highest temperature at which martensite transformation occurs upon 30% true plastic deformation ($M_d^{30}$),

$$M_d^{30} = 413 - 462(C+N) - 9.2(Si) - 8.1(Mn) - 13.7(Cr) - 9.5(Ni) - 18.5(Mo),$$

Applying this equation to the studied 304L, 316L and 6% Mo steels showed that transformation to martensite upon plastic deformation requires a temperature of about 57°C and 8°C for the 304L base metal and its weld metal, respectively. The corresponding temperatures for the 316L base metal and its weld metal are -15°C and -30°C, respectively. As for the 6% Mo steel and its weld metal these temperatures are -90°C and -140°C, respectively. Since testing of the investigated materials was conducted at room temperature the formation of strain induced martensite would take place only in the case of 304L base metal steel [9] and would be excluded from the rest of the tested materials. On that account, generation of stacking faults is expected to be the main deformation mechanism during tensile testing of the remaining investigated materials as well as the 304L base metal steel.

Stacking faults are created in face centered cubic structures during deformation by alteration of the sequence of the stacked layers of atoms. Stacking faults are enclosed by dissociated dislocations and can be looked upon as four layers of hexagonal close packed structure. Because stacking faults are internal surfaces, energy is required to produce them. Such energy is referred to as the stacking fault energy (SFE). The lower the value of SFE the larger the widths of the stacking fault. SFE is an intrinsic property of metals and alloys and is independent of temperature but is influenced by the type of alloying elements. The value of SFE determines the density of stacking faults and governs the distribution of dislocations during deformation. Because of energy constraints, when SFE is low, dislocations that contain stacking faults must move along a given slip plane (the plane along shear deformation occurs). This type of deformation is termed planar deformation and is associated with high rates of work hardening and greater susceptibility for stress corrosion cracking. For high SFE values, it becomes easy for dissociated dislocations to associate, due to the small stacking fault width, and cross slip from one slip plane to the other.
This type of deformation is called cross-slip deformation and is linked to low strain hardening rates and reduced susceptibility for stress corrosion cracking [10].

The effect of alloying elements on the value of SFE of austenitic stainless steels has been the subject of numerous investigations. There is a broad agreement that nickel and copper and molybdenum increase the SFE of austenitic stainless steels and that this parameter is lowered by the addition of chromium and manganese [11, 12]. In relation to the interstitial elements, it has been reported that the SFE is raised by carbon and decreased by nitrogen, both elements exerting a powerful effect [13]. An example, which shows the effect of alloying elements on the SFE of austenitic stainless steels is illustrated in Fig. (2).
steels, is the addition of molybdenum to the commercial 304L steel to form 316L steel. The SFE of AISI 304L was reported to have a value of 18 J/m$^2$. This is to be compared with 78 J/m$^2$ for AISI 316 [11]. These values show that the SFE of the more stable grade 316 steel is about four times as much as that of the less stable 304L steel.

Comparison of the composition of tested base metals and their weld filler materials, Table 1, indicates that there could be a kind of interplay between the alloying elements in determining the SFE of each alloy. The relatively higher content of Ni and Mo in the 6% Mo alloy suggests higher magnitude of SFE than that of 304L and 316L alloy. However, the presence of nitrogen could play a very strong effect in reducing this value. TEM (transmission electron microscopy) observation of fatigued SUS316 austenitic stainless steel containing 0.23 % nitrogen and 2.2 % molybdenum [14] showed planar array of dislocations (a clear indication of reduced SFE). That was attributed to the segregation of Mo-N pairs, as was observed by FIM (field ion image), to stacking faults [14]. Correspondingly, it can be suggested that the SFE of the 6%Mo steel has been lowered due to its relatively high N content to become comparable to that of the 316L steel that accounts for its high value of strain hardening exponent, strain hardening capacity and reduction in area.

The composition of the weld filler metal for the 6%Mo steel (Table 1), reveals that it is a nickel-base alloy, containing about 58% Ni, 25% Cr and 15% Mo. This alloy is designated (alloy 625) and upon solidification, i.e. in the as welded condition its microstructure consists of austenitic matrix with small amounts of interdendritic second-phases [15]. The SFE value of this alloy would be the resultant of the competition between the positive role-played by Ni and Mo in raising the SFE and the negative role-played by Cr in lowering the SFE. The 6% Mo-weld metal showed the highest tensile strength level of all tested materials (Table 2 and Fig. 1). This could be attributed to solid solution hardening effect of the higher Mo and Cr contents (Table 1).

Mo is known to play a potent role in solid solution strengthening of steels compared to other alloying elements as chromium and manganese. This effect is accounted for by the large mismatch in the atomic size between molybdenum and iron [3].

The higher strength and lower ductility levels of the 316L weld metal, as compared to those for 316L base metal, could be attributed to a variety of factors. 316L base metal had received a solution annealing heat treatment, while 316L weld metal was tested in the as-welded condition. This would incorporate residual stresses to the microstructure of 316L weld metal increasing the strength and decreasing the ductility. In addition, the welding filler material of the 316L weld metal has a ferrite content of 10%. The presence of ferrite within the austenite matrix is known to have a strengthening effect [16], which adds to the higher strength level of 316L weld metal. This interpretation extends to the 304L weld metal since it contains about 5% ferrite which accounts for its higher strength values and lower strain hardening capacity as compared to the 304L base metal (Table 2).

In addition, the microstructure of the weld metal of the 6%Mo (alloy 625) steel in the as welded condition was reported to contain small amounts of interdendritic second-phases [15]. The high content of the alloying elements (15% Mo, 25% Cr) would make alloy 625 prone to the formation of intermetallic compounds, such as sigma phase, during cooling through the 900 to 700 °C range [17]. Because sigma phase is chromium and molybdenum- rich together with being hard and brittle, it affects the mechanical properties. On the other hand, sigma phase increases room temperature tensile strength and decreases ductility because of the developed cracks during deformation this leads to premature fracture before necking takes place and hence the ductility is reduced. The superiority of the ductility of 6% Mo base metal over its weld material could be ascribed to the presence of nitrogen (Table 1). It has been found that the addition of nitrogen to molybdenum bearing austenitic stainless steels suppresses the formation of the deleterious sigma phase by increasing the incubation time for intermetallic precipitation reaction [17].
2 Ranking of Elastic-plastic fracture toughness (JETT) of investigated materials:

The JETT (J-Evaluation on Tensile Testing) as calculated from the results of tensile testing of round notched specimens showed that the 6% Mo weld metal ranked highest (1050 kJ/m²) while, the 316L weld metal ranked lowest (480 kJ/m²), regarding JETT fracture toughness values (Table 3). Moreover, Table 3 shows that the tested materials in the base metal condition display higher JETT values over that of their corresponding weld metal condition. As can be seen this only applies for the 304L and 316L conditions. On the contrary, the 6% weld metal condition exhibits higher JETT value than that of its corresponding 6%Mo base metal. Since JETT expresses the elastic-plastic fracture toughness value, its extent is related to the amount of the exerted amount of plastic deformation. In view of the tensile test, the amount of plastic deformation is the resultant of the extent of the tensile strength and plastic strain. Recalling (Table 2), it can be seen that the 6% weld metal acquires the highest tensile strength values as well as high strain hardening exponent (0.32) and strain hardening capacity (0.74). The integration of these parameters leads to the highest JETT value (1050 kJ/m²) among the tested materials. This can be a direct consequence of having higher content of alloying elements (58% Ni, 25% Cr and 15% Mo) which leads to elevating the strength level through solid solution hardening and increasing the work hardening capacity due to reducing the stacking fault energy into an intermediate value. It can also be noted that although the 304L base metal has higher strain hardening exponent (0.35) and higher strain hardening capacity (0.66), its much lower tensile strength leads to lower value of JETT value (850 kJ/m²).

The reduced JETT value of 304L and 316L weld metals can be a result of having 5% and 10% ferrite content respectively, which leads to lowering the amount of the strain hardening exponent, 0.22 and 0.18, respectively and reducing the value of the strain hardening capacity, 0.78 and 0.87, respectively.

It should be noted that the values of the JETT index obtained from this investigation by using round notched tensile specimens is much higher than those obtained from standard methods for elastic-plastic fracture toughness evaluation. As an example, the fracture toughness of the 316L austenitic stainless steel base metal, as measured by using standard compact tension specimen test was about 350 kJ/m² [18].

This is to be compared with a value of 600 kJ/m² evaluated from the current round notched tensile test. This can be attributed to the difference of the plastic zone volume [19] generated ahead of the sharp crack tip of the compact tension specimen and that ahead of the much blunt notch of the round notched tensile specimen Fig. 3. The notch root of the tested tensile specimen of this study equals 0.75 which represents much higher plastic deformation zone causing higher value of ductile fracture and hence higher fracture toughness. Additionally, the difference in the specimen size leads to a difference in the stress state of the standard compact tension specimen and the notched tensile specimen. In the case of the compact tension specimen, which is of larger cross section the stress state is mainly of plane strain which tends to lessen the degree of ductile fracture. Decreasing the specimen size as in the notched tensile specimen increases the percentage of the specimen cross section which is under plane stress, a condition which promotes ductile fracture by minimizing constraint [20].
CONCLUSIONS

- The weld materials of the 304L, 316L and 6%Mo show superior tensile strength and lower tensile strain ranges than the base metal.
- The 6% Mo weld metal and 304L base metal have the highest and the lowest yield and tensile strength, respectively.
- The 304L base metal displays the highest strain hardening capacity ($\sigma_y/\sigma_u=0.66$) while the 316L weld metal has the lowest value ($\sigma_y/\sigma_u=0.87$).
- The strain hardening exponent value as evaluated by uniform strain (strain at maximum load) was also highest for 304L base metal ($n=0.35$) and lowest for 316L weld metal ($n=0.18$).
- The highest reduction in area was displayed by the 6%Mo base metal (RA% = 75%) while the 316L weld metal showed the lowest value (RA% = 30%).
- The 6% Mo weld metal ranked highest (1050 kJ/m$^2$) while the 316L weld metal ranked lowest (480 kJ/m$^2$) regarding JETT (J-Evaluation on Tensile Testing) elastic-plastic fracture toughness values.

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