Effect of welding on impact toughness of butt-joints in a titanium alloy

Wei Zhou a,*, K.G. Chew b

a Division of Engineering and Applied Sciences, Harvard University, 9 Oxford Street, Cambridge, MA 02138-2901, USA
b School of Mechanical and Production Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

Received 30 November 1999; received in revised form 29 July 2002

Abstract

Impact toughness of a gas tungsten arc welded Ti–6Al–4V alloy butt-joint was evaluated at room temperature using standard Charpy V-notch specimens. The Charpy specimens were prepared with notch roots located either in the parent metal, in the heat-affected zone (HAZ), or in the weld metal. Optical metallography and Vickers microhardness test showed that the weld metal has the coarsest grains and highest microhardness compared with the HAZs and parent metal. However, Charpy impact toughness of the weld was found to be more than 50% higher than that of the parent metal or HAZ. The significant improvement in impact toughness was shown to be due to the much reduced amount of primary α grains in the weld metal. Boundaries of primary α grains were observed to be preferential sites for microcrack nucleation and provide relatively easy path for fracture propagation.

Keywords: Titanium alloy; Welding; Heat-affected zone; Impact toughness; Fracture

1. Introduction

Welding of titanium alloys is difficult because titanium is extremely chemically reactive at high temperatures. During welding, titanium alloys pick up oxygen and nitrogen from the atmosphere easily. Studies have shown that the increase in [O] and [H] in the weld increases its strength but at the expense of toughness [1–3].

In the present study, a Ti–6Al–4V alloy was welded by gas tungsten arc welding (GTAW or TIG) technique using a filler metal of similar chemical composition to the parent metal. Pre-welding cleaning procedures and steps to protect the molten weld zone were carried out to avoid contamination of the weld.

Standard V-notch Charpy specimens were machined from the welded joint with their notched roots located in the base metal, heat-affected zone (HAZ) and weld metal respectively. These Charpy specimens were tested at room temperature using a drop weight impact tester. It is interesting to note that impact toughness of the weld metal is more than 50% higher than that of the parent material. The impact toughness of the HAZ was also noticeably higher than the parent material.

Optical and microhardness study of the welded joint revealed that the weld consists of the largest grains with the highest hardness. Therefore, there is no apparent reason to believe that the more brittle weld would have the highest impact toughness. Strong evidence was obtained through examining the crack propagation path using metallographic samples sectioned from the tested specimens to show that the improvement in the weld resistance was due to the microstructural differences among the three zones in the welded joint.

2. Experimental procedures

Specimens used in the investigation were extracted from a butt-welded joints of a Ti–6Al–4V titanium
alloy. At room temperature, the parent metal was found to have a yield strength (at 0.2% offset) of 929 MPa, ultimate tensile strength of 989 MPa, elongation of 14.5%, and reduction in area of 17.3%. The filler rod used during the gas tungsten arc welding was also of the Ti–6Al–4V composition. It has a diameter of 3 mm and satisfies the ASTM Grade 5 specification for Ti–6Al–4V. Chemical compositions for the parent metal and filler rod are shown in Table 1.

High purity argon was used as shielding gas during welding and as trailing gas right after welding to prevent absorption of oxygen and nitrogen from the atmosphere. The titanium alloy plate was 15 mm thick, so multiple welding passes were deposited. The major welding parameters are summarized in Table 2.

Standard Charpy V-notch impact specimens were machined in accordance with ASTM E23-96 specification. The Charpy specimen has a square cross-section (10 × 10 mm²) and contains a 45° V notch, 2 mm deep with a 0.25 mm root radius. All the specimens were obtained in the same orientation from the welded joint. Notch roots were located in the base metal, HAZ, and weld metal respectively such that the general crack propagation was always in the plate thickness direction. A Dynatup 8250 Impact Tester was used to carry out all the impact tests. Impact testing of the Charpy specimens was performed at an impact velocity of 5.25 m s⁻¹ in ambient environment using a tup capacity of 44.482 kN.

Vickers microhardness measurement was taken for the base metal, HAZ and weld metal by a diamond pyramid indenter under a 300 mg load using the Matsuzawa DMH-2 Microhardness Tester before impact testing. After impact testing, fracture surfaces of the notched specimens were examined carefully under the optical microscope and SEM. The sectioning was carried out using a slow speed diamond cutter. The sectioned samples were cold-mounted, ground on SiC paper, electropolished and chemically etched for observation using the optical microscope and SEM. The electropolishing was performed in an electrolyte of 900 ml acetic acid (99.8%) and 100 ml perchloric acid (60%) at 25 V for about 1 min. Etching was carried out in a solution of 5% HF, 20% HNO₃ and 75% glycerol for approximately 30 s.

### Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Al</th>
<th>V</th>
<th>Fe</th>
<th>O</th>
<th>N</th>
<th>C</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent plate</td>
<td>6.38</td>
<td>4.07</td>
<td>0.19</td>
<td>0.17</td>
<td>0.008</td>
<td>0.012</td>
<td>Bal.</td>
</tr>
<tr>
<td>Filler rod</td>
<td>6.10</td>
<td>3.99</td>
<td>0.18</td>
<td>0.13</td>
<td>0.01</td>
<td>0.02</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

3. Results and discussion

Results obtained from the Charpy impact testing are illustrated in Fig. 1. It can be seen from the figure that the weld metal has the highest absorbed impact energy, followed by HAZ and the base metal. The high impact energy observed for the weld is well supported by the fractographic observation. Fig. 2 shows clearly that the fracture surface of the tested Charpy specimen notched in the weld has a tortuous appearance. The longer distance covered by the crack path in the weld compared with that in the base metal or HAZ (Fig. 3) led to the higher energy consumption during fracture propagation.

Fig. 4 shows the fracture surface of a tested specimen notched in the weld after impact testing. It can be seen clearly from the figure that the fracture surfaces contain many dimples. The tested specimens notched in the base metal and HAZ also revealed dimpled fracture surfaces as shown in Fig. 5, verifying that the impact fracture mode was predominantly ductile in all the three zones of the welded joint. However, the dimples were observed to be the smallest in the fracture surface of the weld specimen (Fig. 4). More energy per unit area might be required to produce the smallest-sized dimples.

It is worthwhile to note that the filler metal has similar chemical composition to that of the base plate, but impact fracture toughness was measured to be considerably higher in the weld than in the base material. Metallographic observation revealed the microstructure in the weld to consist of very large grains, as shown in Fig. 6. Grain size can have profound influence on the impact toughness of materials. However, impact toughness is reported to be inversely related to grain size for a given metallurgical condition [4]. Microhardness study of the welded joint revealed that the hardness in the weld (320 HV) was higher than the base metal (280 HV).

On closer examination, it was found that the microstructures were different in the base metal, HAZ and weld. The representative microstructures found in the three zones are given in Fig. 7. Fig. 7(a) shows the base metal to consist of mainly primary α with some alternate α and β platelets. It is noted that during welding, temperature in the HAZ could reach as high as 955 °C and the subsequent air-cooling in the HAZ results in a microstructure consisting of primary α in an acicular α and β matrix, as shown in Fig. 7(b). The temperature of weld must be significantly higher than in
the HAZ during welding. Hence, the microstructure in the weld after air-cooling contains mainly acicular $\alpha$ and $\beta$ with large prior $\beta$ grain boundaries, as observed in Fig. 7(c) [5].

It is now clear that the three zones in the welded joint have markedly different microstructures due to the temperature variations during welding and cooling processes. However, the question remained unanswered as to why different microstructures in the welded joint could lead to the highest impact toughness in the weld metal. Clues to the answer were obtained by observing the metallographic samples sectioned from the tested Charpy specimens.

For the tested Charpy specimens of the parent metal, it was observed under the SEM that many microcracks...
were located close to the main crack path, as shown in Fig. 8(a). Furthermore, the microcracks were invariably found to be located at primary \(\alpha\) grain boundaries or at \(\alpha/\beta\) interfaces. There were a number of studies to show the nucleation of microcracks in dual phase (\(\alpha+\beta\)) titanium alloys during tensile testing [6–9]. However, it seems that the observation of microcrack nucleation at grain boundaries during impact of titanium alloy is
rarely reported in the literature. It is noteworthy that the original microstructure of the base metal was very clean as evidenced in the SEM micrograph shown in Fig. 8(b). Therefore, the microcracks found in the microstructure as shown in Fig. 8(a) must have developed during the impact test, and they coalesced with the main propagating crack during impact testing.

It may be argued that the microcracks could act as crack deflectors to improve the impact toughness. An example of a crack deflection during fracture propagation is shown in Fig. 9. However, the primary α grain sizes in the base metal were noted to be very small in the range of 10–20 μm only. Hence, the grain boundaries or the grain boundary microcracks are unlikely to deflect the fracture path effectively to improve the impact toughness. This is well supported by the fact that absorbed impact energy was measured to be the lowest in the base metal, as shown in Fig. 1.

Metallographic study showed clearly that the HAZ and weld metal contain lower volume percentage of primary α grains than the base metal (Fig. 7). Fractographic evidence was obtained to demonstrate that primary α grain boundaries were favourable nucleation sites for microcracks, and that the microcracks coalesced with the main propagating crack during impact (Fig. 8(a)). Therefore, it is highly plausible to deduce that the improved toughness was due to the absence of microcrack nucleation at primary α grain boundaries in the HAZ and weld during impact test.

Titanium alloys are technologically important structural materials, so there have been many researches on their welding and properties of the welded joints. However, most of the researches are concerned with new welding techniques (e.g. laser welding and electron beam welding) or tensile properties of welded joints, and relatively few researches have been carried out to compare impact toughness of different zones in the welded joints. The work by Lathabai et al. [10] is a notable exception. They measured Charpy V-notch impact toughness values at 20 °C and found that the values are considerably higher for the weld metal than for the base metal, but the material they studied is a commercially pure titanium. Barreda et al. [11] measured crack tip opening displacement (CTOD) of plasma arc welded joints of a Ti–6Al–4V alloy and observed that the maximum fracture toughness was achieved in
the weld metal. They attributed the higher fracture toughness values to the acicular microstructure in the weld metal but did not elaborate on how the acicular microstructure leads to higher CTOD values. In the current study, strong metallographic and fractographic evidence was obtained to explain the phenomenon observed. It would help to understand the mechanisms of fracture better if microscopic fracture stresses [12,13] of the three different zones are measured.

4. Summary and conclusions

Standard Charpy V-notch impact specimens were obtained from a butt-welded Ti–6Al–4V joint. The impact specimens were machined in the same orientation with the notch roots located in the base metal, HAZ and weld metal respectively. Impact tests at room temperature revealed that impact toughness of the weld metal is more than 50% higher than the base metal or HAZ. Fractographic study showed that the crack propagation through the weld is highly tortuous and that the fracture surface contains ductile dimples much smaller than in the base metal or HAZ specimens. Metallographic study showed that the weld is in fact the most brittle part in the welded joint with the coarsest grains and highest microhardness. The base metal was observed to contain primary α grains and some alternate α and β platelets. Due to the heat variations in the welded joint during welding and cooling processes, the HAZ and weld zones formed different microstructures. The HAZ has primary α grains in a matrix of acicular α and β, and the weld has essentially acicular α and β microstructure with large prior β grains. Observation of the sectioned samples from the broken halves of the Charpy specimens showed that during micro-cracks developed at α grain boundaries and coalesced with the main propagating crack in the base metal. The reduced amount of primary α grains in the HAZ and weld metal may account for the improved impact toughness.

Acknowledgements

The authors would like to thank Mr Desmond Tan and Mr C.M. Tay of Singapore Technologies Automotive Ltd for the provision of material, Mr K.C. Soh of Defence Material Organisation (Singapore) for helpful discussion, and Nanyang Technological University for the financial support.

References