CHOSEN METALLOGRAPHIC AND MICROFRACTOGRAPHIC PARAMETERS OF EXPLOSIVELY WEALDED BIMETAL 304 SS AND TI.

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Abstract

The work deals with evaluation of bimetal joint of steel 304SS and commercially pure Ti after explosive welding and next annealing (600°C/1.5 hours/air) with aim to refine the grains of Ti-matrix. Bonding line shows sinusoidal character with noticeable curls in crest unlike the trough of the sine curve. The heat treatment does not change its character. Work demonstrates evaluated chosen metallographic parameters of the joint and its close neighbouring as e.g. wave length, amplitude, thickness of bonding line and parameter of grains compressed thickness between crest and trough, concentrates on analysis of intermetallic particles in the bonding line or in vicinity of joint and micro-fractographic response of joint fracture surfaces after tensile tests. Fracture surfaces shows mixture of both welded matrixes with dominant Ti part and/or practically balanced Ti-Fe portion. Results are confronted with accessible literature pieces of information.

Keywords: Ti-304SS bimetal, interface, intermetallic phase, fracture surface

1. INTRODUCTION

Explosive welding enables to joint directly a wide variety of similar or quite different metals that cannot be joined using any other welding or bonding technique [1-3]. The bonded materials show increased strength, resistance to abrasion and corrosion, or toughness in the applied surface layer of material, whereas the whole product does not necessarily be made from the same material. Bonding methods also significantly reduce material costs. Zimmerly [4] presented the joint of nickel-titanium alloy with low carbon steel by explosive welding and characterised the quality of the resulting bimetal tandem as being an integral part of investigation of protection against erosion. For example Ti and C-Mn steel was evaluated in the paper [5]. However, the primary interest was focused on hardness and microstructure after welding. In work [6] Kaçar reports investigation results of the microstructure-properties relationship in explosively welded duplex stainless steel and steel under as clad condition. With only few bits of information about the 304 stainless steel-titanium sandwich the presented work is focused on some metallographic parameters, intermetallic phases and parameters of bonding line after explosion, respectively after the follow-up heat treatment (HT). The mentioned bimetal finds application in heavy chemical industry.

2. EXPERIMENTAL TECHNIQUE

For study of the 304 stainless steel (304 SS) and titanium (Ti) matrix welded by explosion were used. Titanium was of commercial purity with detected impurities (wt. %): 0.01C, 0.05Fe, 0.050, 0.005N, 0.006H. The 304 SS had the following chemical composition (wt. %): 0.04C, 0.45Si, 1.96Mn, 18.42Cr, 9.74Ni, 0.006P and 0.011S. In EXPLOMET-Opole both materials were explosively welded and subsequently the clad plate was subjected to ultrasonic testing. Tensile tests (joint situated in centre of testing bar) were carried out according to the standard ČSN EN ISO 6892-1 (MTS machine) at ambient temperature. The samples of 304
SS steel and Ti sandwich were machined by mechanical cutting to avoid any change in microstructure. The thickness of the 304 SS and the Ti layer corresponded to 110 mm and to 6 mm (given in sequence). For metallographic evaluation of microstructures, including micro-joints in the welded area, samples of dimension 20 x 20 x 40 mm were made. Specimens for micro-structural examination were prepared by standard metallographic techniques. The bimetal was etched in nitric acid and hydrofluoric acid and in water solution of hydrochloride and nitric acid. The Ti matrix was also etched according to \[7\]. For both material types metallographic evaluation included the wave amplitude and wave length, thickness of the weld, thickness of the deformed Ti matrix near the crest and the trough of the interface, and analysis of the formed phases (inhomogeneities) in close proximity of the weld line. Tensile tests (joint situated in centre of testing bar) were carried out according to the standard ČSN EN ISO 6892-1 (MTS machine) at ambient temperature. Part of solution the micro-fractographic evaluation of fracture surfaces of tensile bars were carried out. The light microscope Olympus X70 and the electron microscope SEM JEOL JSM-6490 LV equipped with energy dispersion analyser (EDA) OXFORD INCA Energy 350 were used.

3. RESULTS AND ANALYSIS

After bonding the bimetal showed yield stress on the level of 410 MPa, tensile strength was 561 MPa and elongation 38%. At lower magnification the micrograph of the as bonded 304 SS - Ti sandwich shows typical wavy interface of the nature as it was also reported \[6, 8\]. After the HT no change in the type of interface occurred. In comparison with the length of the sample (including 6 waves) the average total length of the interface showed difference of 14.2%. On average, the amplitude corresponded to 287 µm and the wave length to 1690 µm. In explosively welded duplex stainless steel with a C-Mn (0.2 and 1.5 wt.%), Kačar et al. \[6\] approximately reached the amplitude of 313 µm and the wave length of 1375 µm. Kačar’s amplitude was by 9% higher than in our case and the wave length was by 19% shorter. Naturally the type of the welded materials, the type of explosives and quantities influencing the collision velocity played a role. In case of brass C-Mn steel Ostroushko \[9\] showed that the wavy interface is sharper in curls of waves reaching to the softer brass in comparison with the trough. In his case the determined amplitude reached 340 µm and wave length 1590 µm \[9\]. The parameters of welding must naturally influence the above mentioned data. Cowan with his co-workers \[10\] showed that an increase of collision velocity, e.g. from 1900 m.s\(^{-1}\) to 2500 m.s\(^{-1}\), resulted in an increase of the wave length and wave amplitude by 50%. The nickel-steel bimetal was in question. The found thickness of the bonding line corresponded to 1.5-2.7 µm. On average it was 1.9 µm, while e.g. Kačar et al. \[6\] reported 1.5 µm in case of duplex steel and C-Mn steel sandwich.

Table 1 Chemical composition of melted zones [at. %]

<table>
<thead>
<tr>
<th>analysis</th>
<th>C</th>
<th>Al</th>
<th>Si</th>
<th>Ti</th>
<th>Cr</th>
<th>Mn</th>
<th>Fe</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>0.31</td>
<td>16.49</td>
<td>16.50</td>
<td>1.49</td>
<td>56.68</td>
<td>8.22</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.44</td>
<td>20.83</td>
<td>15.26</td>
<td>1.34</td>
<td>53.25</td>
<td>8.60</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.18</td>
<td>65.52</td>
<td>4.87</td>
<td>0.56</td>
<td>24.26</td>
<td>4.60</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.15</td>
<td>0.16</td>
<td>63.76</td>
<td>5.18</td>
<td>0.62</td>
<td>25.89</td>
<td>4.24</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>17.55</td>
<td>0.13</td>
<td>0.35</td>
<td>20.1011.8</td>
<td>11.88</td>
<td>1.23</td>
<td>42.30</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>0.31</td>
<td>22.64</td>
<td>14.88</td>
<td>1.55</td>
<td>52.93</td>
<td>4.24</td>
<td></td>
</tr>
</tbody>
</table>
Melted zones, typical phenomenon [6, 11] for most bimetals, were detected, mostly in curls and/or in the close proximity of the 340 SS - Ti interface as it can be seen in Fig. 1 and Table 1. These phases were on the base of Ti-Cr-Fe-Ni, or possibly with Mn and/or with Al, Si or Mo balanced and were revealed by use of the SEM and EDA analyser (analyses 1 and 2 in Table 1). The interface contained Ti (66-68 at. %), Fe (21-25 at. %), approx. 5 at. % of Cr and of approx. 3-4 at. % of Ni. In some cases very low Si and Al contents were also detected. In Table 1 the analysis 3 represents it. In centre of intermetallic area similar chemical composition of analyse 3 was found (marked 4 in the Table 1). The other phases (analyses 5 and 6) were chemically close to the analysis 2. In two cases higher carbon content was analysed. The carbon presence could be explained with some dirt that got to the material during welding or its preparation. At higher temperature than 800°C Ghosh [11] detected molten zones with Ti (60-69 at %), Fe (24 at. % on average) and Cr (approx. 7 at. %) besides the Ni balanced. Similar zones were revealed in work [12] on the Ti-Cr-Fe-Ni base, sometimes with Mn and/or with Al and Si. Any complex oxides were not revealed. After diffusion bonding Ti and steel Ghosh [11] seldom detected Fe₂Ti₄O only, whereas after explosive welding Ti with Ti Berdychenko et al. [13] observed both TiO and TiO₂ or Ti₂O₃ oxides. In second case the interface showed noticeable heterogeneities after etching. On the top of it bimetal Ti and Ti has strong oxygen bond from both interface sides. With continuing weld over the plate length and with higher collision velocity number of heterogeneities has been increase. Typical chemical compositions for λ-phase (Fe₅Ti or Cr₅Ti) or χ-phase (FeTi) were not analysed as it was presented by Ghosh et al. [11]. No σ-phase was also observed unlike the work [11], where Ti with stainless steel was bonded by diffusion in the temperature range of 800-900 °C, when σ-phase could be formed. During explosive welding, the temperatures were much higher and the cooling process ran much faster. However, under those conditions Fe and especially Ti varied widely across the interface and its adjacent zone thanks to the higher diffusion coefficients unlike the Ni. On the other hand, the Ni atoms can travel a longer distance in Ti matrix due to higher crystallographic bcc structure [11, 14]. It could be also the reason of a detection of quite new intermetallic phases as it was reported in [6, 11, 14].

In close vicinity of interface or direct in bonding zone none cavities were also detected. It could be explained by the explosion welding parameters, especially by enormous pressures at the interface of both materials. The existence of cavities was predominantly observed in the temperature range of 700-850°C [11, 14]. Defects of cracks type and un-joined areas were not observed, either. Mamalis [15] found those defects in the case of Al-Cu, Ag-CdO-Cu sandwiches unlike the Ni-Ti bimetals [10]. At low collision velocity the
interface is straight and smooth practically [10] in comparison with higher collision velocity when the weld line becomes wavy. Then the in-homogeneities in a form of melting zones begin to appear under the curls of waves. The reason is the kinetic energy dissipation at collision process being the reason of melting zones formation at the interface and in adjacent areas. According to Cowan [10] 10-30% of the kinetic energy is spent as a necessary energy for the interface area formation and under extreme high cooling rates heterogeneities in chemical composition, very often connected with new intermetallic phases, can be expected. As the work [10] refers it, the main sources of the phenomena is the detonation temperature, material heating being a result of high pressure shock leading to severe plastic deformations and adiabatic heating of gases compressed between the bonded materials.

Near the interface, grains of both matrixes were strongly deformed. The microstructures were presented formerly in paper [9]. In 304 SS the detected twins are typical phenomena of this type of material. The higher deformation, the higher density of twins can be expected. In vicinity of bonding line grains are strongly deformed in Ti-matrix, too. In the frame of interface microstructure evaluation, the compressed Ti grains thickness was measured. The crest of wave represents the parameter -b-, whereas the trough of wave is characterised by the parameter -a- as it the Fig. 2 schematically shows. In the Ti matrix the average rate of b/a corresponds to 0.4 and represents differences in various wave levels. The average thickness of the deformed layer was 188.8 µm (b) in the wave crest and 67.2 µm (a) in the wave trough on average. Similar results were reached by Bataev [8] in case of laminate steel 20 (0.2 wt. % C) and steel 60G (0.6 wt. % C) where the b/a ratio was 0.55 on average. The more deformed layer, the higher micro-hardness can be found.

In adjacent zone of interface maximal values were detected.

![Fig. 2. Diagram of evaluated thickness of deformed areas in Ti matrix](image)

**Fig. 2.** Diagram of evaluated thickness of deformed areas in Ti matrix

Figure 3 demonstrates appearance of general fracture surface of tensile testing bar. It indicates the wave character of interface. The detailed fracture surface can be seen in Fig. 4. The carried out analyses proofed the most of fracture surface corresponded to mixture of both matrixes forms with predominant Ti portion as the Table 2 demonstrates (the darker area 2a, b in Fig. 4). The lighter grow colour belongs to mixture matrix with the lower volume fraction of Ti and practically balanced iron portion (area 3a, b). In the lightest areas of fracture surface (1a-1c in Fig. 4 and Table 2) highest volume fraction of iron was revealed in the investigated 304 SS and Ti bimetal. The darkest small spots (a,b in Fig. 4a and 4c in Fig. 4b) present 100 % of Ti. The results in Table 2 did not confirm that the crack initiation and its propagation was predominantly realised in the melt zones which were discussed above (see Table 1). Consequently those have not evidently important detrimental effect in given sandwich.
Table. 2 Chemical composition of fracture surface after tensile tests [at. %]

<table>
<thead>
<tr>
<th>Name</th>
<th>Si</th>
<th>Ti</th>
<th>Cr</th>
<th>Mn</th>
<th>Fe</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>0.62</td>
<td>19.17</td>
<td>16.66</td>
<td>1.55</td>
<td>54.86</td>
<td>7.14</td>
</tr>
<tr>
<td>1b</td>
<td>0.96</td>
<td>19.64</td>
<td>16.69</td>
<td>1.64</td>
<td>54.08</td>
<td>6.99</td>
</tr>
<tr>
<td>1c</td>
<td>1.14</td>
<td>21.09</td>
<td>16.20</td>
<td>1.54</td>
<td>52.76</td>
<td>7.28</td>
</tr>
<tr>
<td>2a</td>
<td>97.08</td>
<td>0.52</td>
<td>2.01</td>
<td>0.39</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2b</td>
<td>95.74</td>
<td>0.72</td>
<td>3.07</td>
<td>0.47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>0.63</td>
<td>45.34</td>
<td>11.26</td>
<td>1.05</td>
<td>36.86</td>
<td>4.86</td>
</tr>
<tr>
<td>3b</td>
<td>0.61</td>
<td>42.15</td>
<td>11.22</td>
<td>1.13</td>
<td>40.25</td>
<td>4.64</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS

The line of interface of explosively welded stainless 304 SS and commercial Ti showed wavy character. On average the amplitude corresponded to 287 µm and the wave length was 1690 µm. The thickness of bonding line was lying on the average level of 1.9 µm.

In the crest of wave the bonding line showed curls unlike the trough of the sinusoidal wave. In the curls various melted zones were detected. At collision process the kinetic energy dissipation is the reason of their formation. Chemical analyses no oxides confirmed. In the melted zones intermetallic phase on Ti-Fe-Cr basis, and possibly with very low Mn, Ni, Si eventually Al portions were detected. Defects of un-joined materials type or cavities were not found. In the vicinity of the wave interface evaluation of compressed Ti grains thickness showed the rate between the crest and trough area (b/a) on the average level of 0.4 (188.8/67.2).
The fracture surfaces of tensile tests bars predominantly showed mixture matrixes, mostly with higher volume fraction of Ti (approx. 96 and/or 45 at. %). In second case Fe the balanced portion forms above all. It proofs the bimetal did not preferentially crack in detected intermetallic phases.

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REFERENCES


