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FORMABILITY CAPABILITIES AND MECHANICAL PROPERTIES OF TITANIUM TAILOR-WELDED BLANKS

SPOSOBNOST OBLIKOVANJA IN MEHANSKE LASTNOSTI IZ TITANA ZVARJENIH PLOČEVIN

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Titanium alloys have many applications in aerospace, nuclear and automotive industries and in most parts are in sheet form and require joints of high integrity to meet the design requirements and achieve reliable welds. For weight and cost reduction, the technology of tailor-welded blanks (TWBs) is a promising technology in various components. TWBs are usually semi-finished metallic sheets made of different strengths, materials, and/or thicknesses and a forming process is often needed to manufacture the final components. In this paper, Grade-2 and Grade-5 titanium alloy sheets (Ti-TWBs) were laser welded and subjected to a forming process in U-profile geometry at elevated temperatures. The deformation behaviors of the weld joints after forming process were analyzed by mechanical tests such as tensile and hardness tests. The formability of the welded blanks is assessed based on variations in the geometric changes related to the springback angles. The results showed that there was significant increase in tensile strength with forming temperature increase and the failure mode was changed at 850 °C. The formability of the Ti-TWBs was found to be strongly dependent on the applied process temperatures and forming at 850 °C leads to the lowest springback angle.

Keywords: titanium, formability, laser welding, mechanical strength, tailored welded blanks

Zlitine na osnovi titana se uporabljajo na mnogih področjih v letalski, nuklearni in avtomobilski industriji. Večina izdelkov iz titana in Ti zlitin se v glavnem izdeluje oziroma oblikuje iz pločevin, ki jih je treba najprej tudi medsebojno zvariti. Zvari morajo imeti visoko integriteto zato, da zadostijo zahtevam oblikovanja in delovanja. Zmanjšanje mase izdelkov in stroškov njihove izdelave zahteva tehnologijo medsebojnega varjenja pločevin (TWBs; angl.: technology of tailor welded blanks). To je obetajoča tehnologija za izdelavo različnih komponent. TWBs so običajno polproizvodi iz različnih materialov in različno debelino, ki jih je potrebno še preoblikovati v finalni izdelek. V pričujočem članku avtorji opisujejo medsebojno lasersko varjenje dveh vrst pločevin iz Ti zlitin (Razred-2 in Razred-5), ki so jih nato še preoblikovali s postopkom vročega stiskanja v U-profile. Po postopku vročega stiskanja so avtorji analizirali potek proces deformacije in določili mehanske lastnosti; i.e.: trdoto in natezno trdnost zvarnih spojev. Preoblikovalnost zvarnih spojev Ti pločevinso avtorji analizirali tako, da so ocenjevali geometrijske spremembe povezane s povratnim vzmetnim učinkom (angl.: springback effect). Rezultati raziskave so pokazali, da pride do pomembnega povečanja natezne trdnosti in spremembe načina loma privročem stiskanju nad 850ºC. Avtorji so tudi ugotovili, da je oblikovanje lasersko varjenih Ti pločevin z vročim stiskanjem močno odvisno od procesne temperature in da vroče stiskanje pri 850 °C vodi do nastanka najmanjšega kota zaradi povratnega vzmetnega efekta.

Ključne besede: oblikovanje titana, lasersko varjenje, mehanska trdnost, oblikovanje varjenih pločevin

1 INTRODUCTION

Despite its high cost, titanium and its alloys are the preferred materials in aerospace, biomedical, and automotive industries due to their mechanical strength, low density, corrosion resistance and excellent creep properties up to 300 °C.[1] Notwithstanding the advantages, since titanium alloys are found in the form of sheets, it also has some manufacturing limitations while fabricating spacecraft, jet engines and automotive bodies. Titanium sheets exhibit low formability and high springback behaviour at room and low temperatures, and this causes many challenges.[2,3] However, there are types with very different properties within the wide range of titanium grades. From the titanium family, the Grade-5 (Ti-6Al-4V) has a higher strength compared to Grade 2; in spite of this Grade 2 has very high ductility, and can be deformed into complex shapes by sheet forming.[4,5]

In recent years, with the rapid development of technology and increasing environmental awareness, technologies in which mechanical properties can be changed in a controlled manner to meet different performance requirements have gained great importance, especially in the automotive industry, as well as lightening studies.[6] For this purpose, tailor-welded blanks (TWBs) are developed to improve safety features, fuel consumption, and crashworthiness when sheets of different grades or materials, various thicknesses and different coatings joined by a welding process prior to forming into the final part geometry.[7] The use of TWB in the auto-body structure can reduce the weight of the vehicle and energy utilization during manufacturing.[8] Titanium in comparison to steel and aluminium in the manufacture of TWBs has enormous potential for the fabrication of lightweight systems

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in various industries with high mechanical demands and improved part performance. There are few studies to evaluate the suitability of titanium as TWB components. Since there is a growing demand for TWBs and obtaining components with a complex geometry and the desired strength and functional properties, more work needs to be done on this subject.

Adamus and Lacki[9] investigated the sheet-metal forming of titanium welded blanks experimentally and numerically. Stress and strain distribution were analysed by forming spherical drawn-parts made of Grade-2 and Grade-5 blanks, and electron beam welded Grade-2 to Grade-5 blanks. Winowiecka et al.[10] evaluated the drawability of Ti- TWBs consisting of titanium Grade-2 and Grade-5 alloys, and thinning was observed in Grade-2 sheet metal close to the weld. This paper aims at investigating the effects of tooling temperatures on the formability of Ti-TWBs at elevated temperatures. Lai et al.[11] employed a newly developed tooling system with a heating-control function in their investigation. TWBs with different thickness combinations examined for formability under elevated temperatures. Karpagaraj et al.[12] studied the formability limits for titanium Ti–6Al–4V alloy TWB sheets having a thickness of 1.6 mm and 2 mm; in addition to that, microstructural studies were carried out to understand the effect of the GTAW process. The quality of the weld was examined through metallographic (macro- and micrographs) analyses and mechanical tests.

In this respect, the weldability and post-weld formability of titanium alloys have become very important for many sectors. Laser welding is the most preferred process for tailored blank applications because of its high welding speed, high precision, small heat-affected zone and ease of interface with robots.[12–16] CO_2 and Nd:YAG lasers were traditionally the welding processes mainly used for TWB applications.[17–19]

Numerous studies can be found in the literature that examine the weldability of titanium and its alloys.[20–24] Fomin et al.[25] carried out an experimental study on the metallurgical and microstructural characterization of laser-beam-welded T-joints between commercially pure titanium and Grade-5 alloy. Because of the poor deformation capability of titanium alloys at room temperature, they are mostly formed in hot-forming processes. Therefore, most investigations are focused on the mechanical properties of titanium alloys at high temperatures. However, recent advanced forming methods enable them to form at room temperature. Li et al.[26] investigated the deformation characteristics, formability and springback characteristics of titanium alloy sheets at room temperature. Mainly the deformation characteristics of titanium alloys at room temperature are discussed. Ramadass et al.[27] conducted experimental and numerical studies on the formability of Grade-2 titanium sheets using the Erichsen cupping test method. Zhu et al.[28] investigated the formability of commercially pure titanium Grade-2 foils to determine the optimum forming process. The influences of geometry, temperature and high-velocity impact were examined to ensure a better understanding of their impacts on the formability of the foils. Campanella et al.[29] carried out a comprehensive study to understand the effect of various production methods on titanium Grade-5 parts. This study focused on aeronautical parts and two different geometries were used. Results were evaluated in terms of mechanical, geometrical, and microstructural aspects. Ertan and Çetin[30] investigated the deformation temperature's effect on the mechanical properties and springback behavior of Grade-5 titanium sheets. Tekin et al.[31] examined the springback behavior and mechanical properties of Grade-2 titanium sheets, which were hot formed at elevated temperatures.

In the present study, Grade-2 and Grade-5 Ti alloy sheets with 1 mm thickness were laser welded and deformed to fabricate Ti tailor-welded blanks (Ti-TWB). The mechanical properties were investigated through tensile and microhardness tests. Further, the effect of forming temperature on the formability was studied by the 3D scanning method with springback angle measurements of the U-profile.

2 EXPERIMENTAL PART

2.1 Materials

Materials used are rolled sheets of 1-mm-thick, commercially pure, Grade-2 and Grade-5 titanium alloys. The chemical composition of the materials is presented in **Table 1**.

Table 1: Chemical composition of Grade-2 and Grade-5 titanium alloys

	Fe	O	C	N	H	Al	V
Grade-2	0.3	0.25	0.08	0.03	0.015	–	–
Grade-5	0.3	0.2	0.1	0.05	0.0125	6	4

2.2 Laser Welding

Grade-2 and Grade-5 titanium alloys sheets were primarily cut into blanks with a size of 330 mm × 125 mm × 1 mm in the specimen-preparation process. The blanks' length direction was along the rolling direction. Prior to welding, the plates were mechanically ground and cleaned with acetone. The Grade-2 and Grade-5 sheets were clamped adjacent to each other in a fixture to guarantee the correct alignment during the laser welding. The welds were performed in the flat position with a butt joint and without adding filler material.

To prevent the entry of air into the welding zone and to protect the welding seam from the adverse effects of air, high-purity argon gas is preferred as the shielding gas. The welding operation was carried out by means of a SISMA SWA-300 Nd:YAG laser-welding machine, whose main characteristics are mentioned in **Table 2**.

Table 2: Laser-welding process parameters for welding Grade-2 and Grade-5 alloys

Process	Average power	Peak power	Pulse energy	Pulse duration	Spot diameter	Laser beam transport
Nd: YAG laser welding	0.3 kW	12 kW	30.6 J	3.6 ms	1.3 mm	Fiber-coupled

Table 3: Mechanical properties of Ti-TWB specimens before and after forming process

Type of specimens	Process stages	0.2 % yield strength (MPa)	Ultimate tensile strength (MPa)	Total strain (%)
Grade-2	No welding, no forming	280.0	344.0	18
Grade-5	No welding, no forming	927.5	957.8	10
Weld	Welding (Grade-2 – Grade-5), no forming	351.0	372.2	9.39
WF1	Welding (Grade-2 – Grade-5) and forming (RT)	-	170.0	0.95
WF2	Welding (Grade-2 – Grade-5) and forming (500°C)	309.8	313.4	4.1
WF3	Welding (Grade-2 – Grade-5) and forming (850°C)	336.4	373.1	12.9

2.3 Forming Process

After the welding process, the joints were heated to 550 °C and 900 °C for 10 min in a conventional furnace, directly transferred to the press and subsequently formed. The transfer time from the furnace to the cold die was 5 s, and the temperature drop was 50 °C. The forming process was carried out in U-profile die for Ti-TWBs in a 200-tonne hydraulic press with 10 mm/s punch speed. The blanks were formed and held for 1 min in the dies. During the forming of the welded blanks there was not a loss of material cohesion nor any fracture in the weld zone or base material. The experimental setup is shown in **Figure 1a**, in which the punch and die were made by a tool steel. The welded specimens were placed after aligning the weld-line parallel to the center of the U-profile die with the weld top surface facing the punch (**Figure 1b**).

2.4 Test Procedure

Tensile and hardness tests were conducted to observe the mechanical properties of the Ti-TWBs formed joints. All the tests were performed at room temperature. The samples were cut from the bottom of the welded U-profile (**Figure 1b**) using a 3-axis water jet (Robojet) according to the ASTM-E8 standards. Test specimens had standard dimensions of 140 mm in length and 20 mm in width. Tensile tests were conducted under standard laboratory conditions, specifically at room temperature, utilizing a cross-head speed of 2 mm/min. These tests were conducted using a Zwick/Roell 100-kN universal tensile-testing machine. The Vickers hardness test was carried out employing an indentation load of 0.5 kg and a dwell time of 10 s, utilizing an EmCo hardness test machine. Each sample underwent hardness measurement at five distinct points, ensuring comprehensive data collection across the sample surface. Subsequently, the average hardness values were calculated to provide a representative assessment of the material's hardness characteristics. Dimensional data of the U-profiles were obtained using the Faro-Quantum Max FaroArm 3D scanner. This data was utilized to analyse the springback behavior of the profiles, providing valuable insights into their structural response to forming processes. The scanned data were integrated into the CAD data using CATIA V5 software, facilitating the visualization and analysis of the combined data sets.

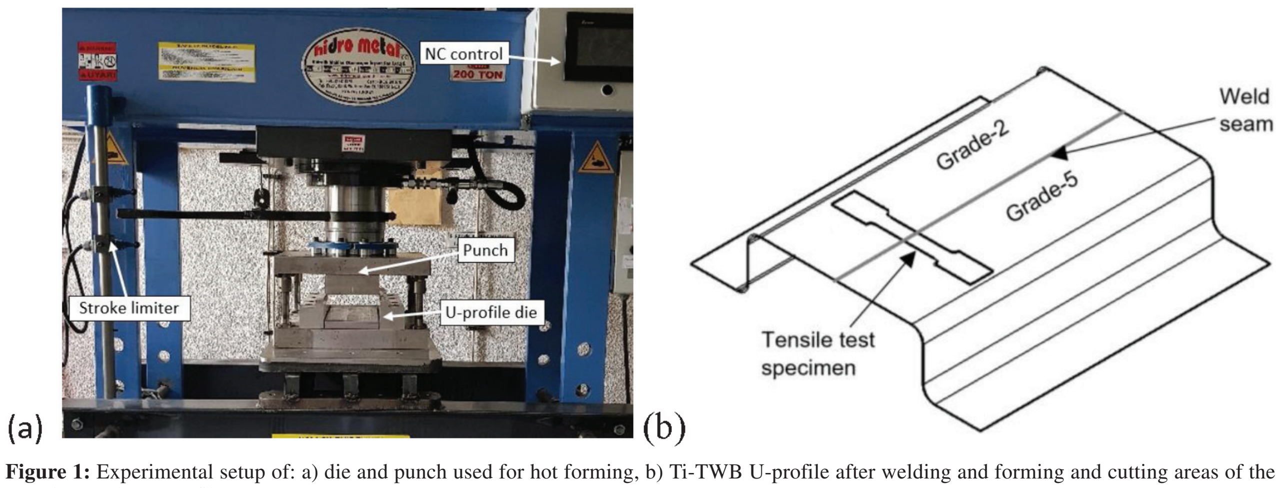

Figure 1: Experimental setup of: a) die and punch used for hot forming, b) Ti-TWB U-profile after welding and forming and cutting areas of the samples on the U-profile

3 RESULTS AND DISCUSSION

3.1 Mechanical Properties

The specimens of Ti-TWBs formed as U-profile at room temperature (RT), 500 °C and 850 °C were subjected to tensile tests at RT. The tensile deformation is performed using three specimens for each group. The data presented in **Table 3** represents average values. The results are given and compared in **Table 3**. It is observed that the Grade-2 sheet was more ductile than the Grade-5 with more elongation. The yield strength and ultimate tensile strength of the Ti-TWB were very close to Grade-2 sheet metal. The Grade-2 sheet material was ductile enough to withstand the deformation during a uniaxial tensile test due to the presence of a harder weld zone. The results show that the yield strength and tensile strength increases related to the forming temperature increasing. This is thought to be due to heating before forming reduced the residual stresses inside the weldment and the drawability and mechanical properties were improved with stress relieving in Ti-TWBs.[11]

As shown in **Figure 2**, the tensile strength of the specimens was slightly increased with increasing forming temperature up to 850 °C. In the welded specimens formed at room temperature, the fracture occurred in the elastic region with a very small elongation of 0.95 %, and before reaching the yield stress point. The strength increased dramatically about 84 % up to 500 °C, which indicates adequate penetration in the weld area and stress relieving due to heating before forming.[32] While a significant increase in elongation has not occurred up to 500 °C, it was increased considerably to around 21 % between 500 °C and 850 °C forming the start temperature. The slight increase of around 19 % in tensile strength between 500 °C and 850 °C also supports this, due to the softening effect of recrystallization in comparison to the no-forming condition. In the literature, the recrystallization temperatures for Grade-2 and Grade-5 Ti alloys were investigated by some researchers for the same forming parameters as the present study. Tekin et al.[31] have found that dynamic recrystallization appeared at 550 °C forming a start temperature in Grade-2 Ti alloy. However, the recrystallization temperature for Grade-5 Ti alloy was described approximately at 750 °C by Ertan and Çetin.[30]

The change of the elongation of Ti-TWB specimens in Grade-2 and Grade-5 side, after the forming process at different forming start temperatures (RT, 500 °C and 850 °C) is shown in **Figure 3**. It is clear that specimens formed at room temperature exhibited an elongation mostly in the Grade-2 side of the Ti-TWBs and welding seam before forming was shifted 4.8 mm towards Grade 5. This is because Grade 2 is more ductile than Grade 5 at low temperatures. The elongation after the forming at 500 °C of the weldments occurred mostly on the Grade-2 side. The location of the weld seam was displaced 204 % more than the specimen formed at room temperature. The high increase in ductility of Grade-2 at 500 °C is thought to be due to recrystallization. However, it is seen that the formed sheets at 850 °C elongate more on the Grade-5 side. Although it is thought that there is an elongation in both materials at this temperature, there was a displacement of the weld seam towards Grade 2 due to an effective recrystallization event on the Grade-5 side. This is because Grade 5 is recrystallized at approximately 750 °C, and its ductility changes at these temperatures. However, there was no separation in any of the welds during forming in or outside the welding area.

During the tensile tests of the Ti-TWBs formed at RT and elevated temperatures, two types of failure occurred. The specimens formed at RT and at 500 °C forming start temperature were fractured at the weld. But the specimens formed at 850 °C forming start temperature were fractured from the Grade-2 side, as seen from **Figure 4**. The failure of specimens in the tensile test occurred on the Grade-2 side with a distance of approximately 30

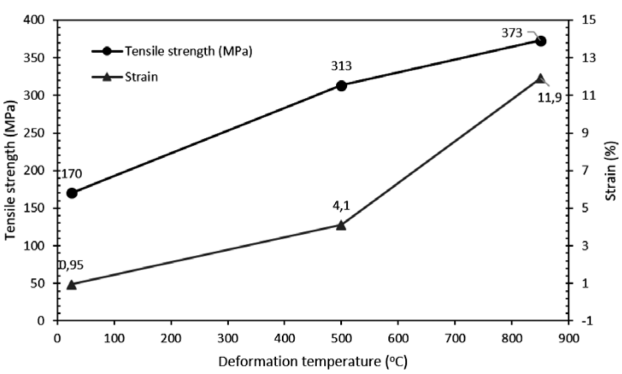

Figure 2: Effect of deformation temperature on tensile strength and total strain in Ti-TWBs

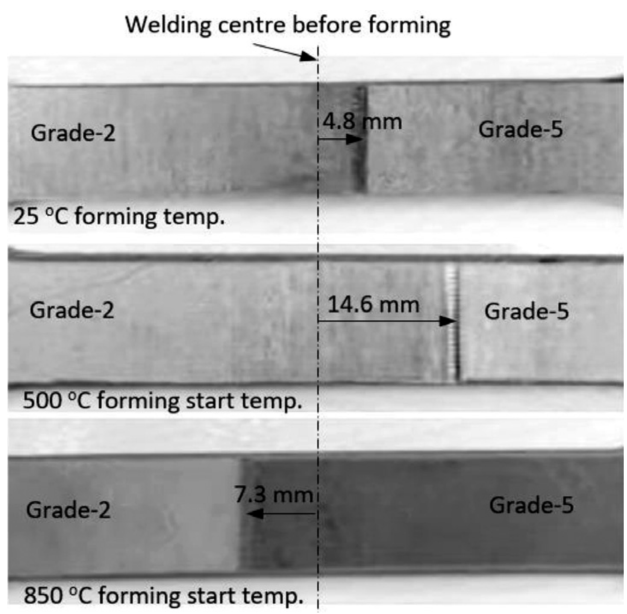

Figure 3: Displacement of the weld seam from the centre during forming Ti-TWBs at different temperatures (RT, 500 °C and 850 °C)

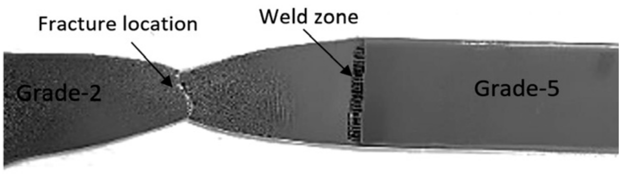

Figure 4: Failure mode of the Ti-TWBs formed at 850 °C

mm from the weld. In **Figure 4** it is shown that the ductile failure took place due to localized necking after the onset of diffuse necking in the Grade-2 sheet. In welded joints, it is expected that the fracture will occur from the weaker material region. This confirmed the good quality of weld without any major defects. In addition, it is thought that the shaping process at 850 °C reduces the stresses in the weld area with the effect of heat treatment and increases the penetration with the effect of diffusion. It was observed that the high forming temperature after welding has a significant influence on the strength and elongation.

Figure 5 shows the microhardness distribution of LBW Ti-TWBs for Grade-2 to Grade-5 welds after the forming process at RT, 500 °C and 850 °C start temperature conditions. It was found that the Grade 5 was much harder than the Grade 2 because of the presence of alloying elements like aluminium and vanadium.[15] The hardness of the weld zone (WZ) varies between 258 and 307 HV was was higher than the Grade-2 base material hardness (140 HV) and lower than the Grade-5 base material hardness (335 HV) in all specimens. This is due to the diffusion of alloying elements from the Grade-5 side to the Grade-2 side.[33] It is seen that this behavior continues towards the Grade-2 side and the hardness is higher in the areas closer to the weld zone. Especially in the samples formed at the 850 °C start temperature, with the increase of weld penetration. As a result of the deformation process at 500 °C, a significant decrease in hardness occurred compared to room temperature and 850 °C. This decrease supports the ductility increase obtained as a result of the tensile test (**Figure 2**) and the elongation on the Grade-2 side of the formed welds. The hardness in the Grade-5 side of the formed Ti-TWBs was decreased with forming temperature increasing. The average hardness value was reduced from 333 HV to 317 HV and to 302 HV with a forming-temperature decrease from RT, 500 °C and 850 °C, respectively.

3.2 Springback Behavior

The springback behaviors of Ti-TWBs formed at different temperatures are given in **Figure 6**. By comparing the profile of the U-bending parts formed at different temperatures, it is found that the springback angle was reduced and formability increased significantly with forming temperature increasing. According to **Figure 6**, the lower springback angles and higher dimensional accuracy were achieved on the Grade-2 side compared to Grade-5 side of the weldments. As known from the literature, Ti alloys have a hexagonal close-packed crystal structure with a limited number of slip planes. For this reason, Ti has lower formability at RT, but at high temperatures, the existence of alternative slip systems improves the formability.[26] According to **Figure 2**, the strength of the Ti-TWBs after the forming process generally increases as the temperature increases. On the other hand, the hardness decreased with the deformation temperature increased and the plastic deformation capabilities was increased (**Figure 5**). The springback angles in different positions were decreased with forming start temperature increasing in both the Grade-2 and Grade-5 sides of the formed Ti-TWBs. However, while this decrease was more on the Grade-2 side at 500 °C, it occurred at 850 °C on the Grade-5 side of the weldments. The reductions in springback angles $\beta 1$, $\beta 2$ and $\beta 3$ were

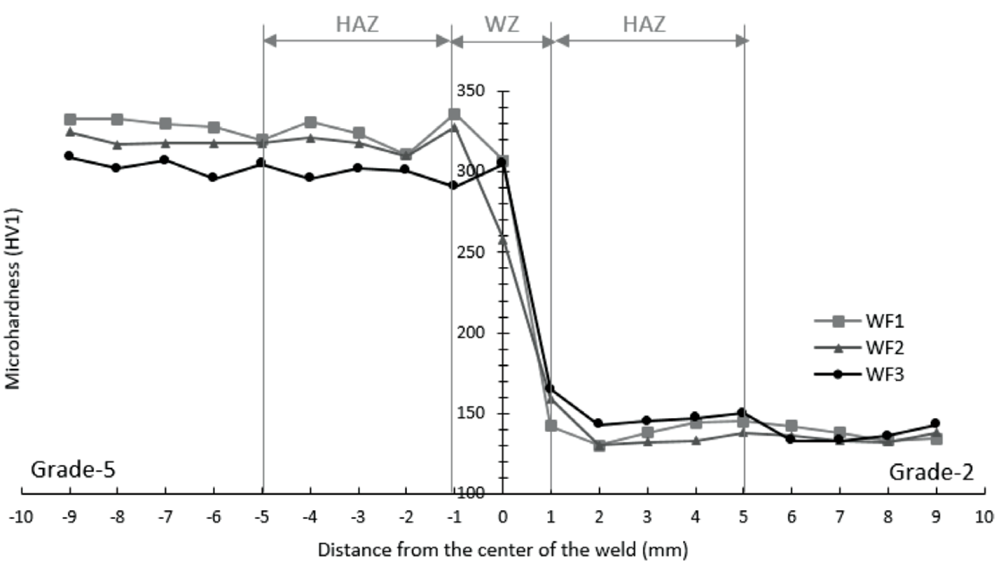

Figure 5: Microhardness profile along the cross-section of the Ti-TWB specimens

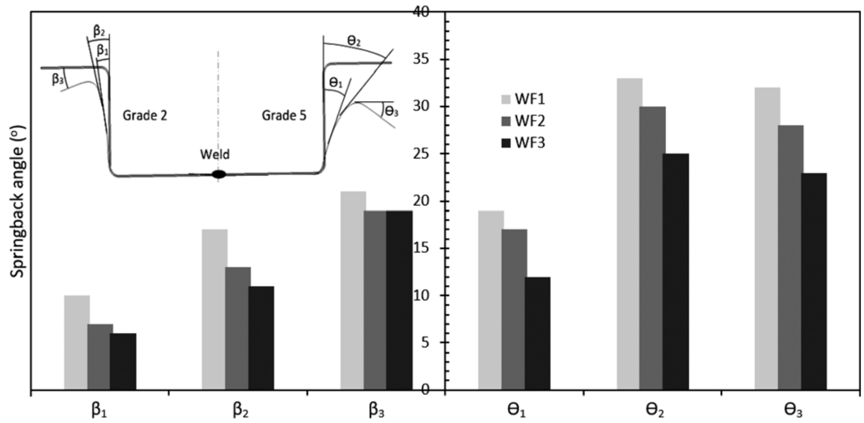

Figure 6: Effect of forming start temperature on springback angles in Grade-5 side and Grade-2 sides of Ti-TWBs

around 30 %, 24 % and 10 %, respectively, at the forming start temperature at 500 °C compared to forming at room temperature. On the Grade-5 side, the Θ1, Θ2 and Θ3 springback angles decreased by 37 %, 24 % and 28 %, respectively, at 850 °C compared to room temperature. These results were obtained in accordance with the tensile test and hardness test results.

4 CONCLUSIONS

The present study investigates the mechanical properties and springback behavior of dissimilar welded and formed titanium Grade-2 and Grade-5 materials using laser welding. Based on the test results the following conclusions were drawn:

Increasing the forming temperature resulted in an increase in welding penetration. Additionally, the tensile strength improved and the strain increased considerably at 500–850 °C forming start temperature. In weldments formed at room temperature, fractures occurred before reaching the yield point. With the increase in forming temperature to 850 °C, residual stresses decreased, and the tensile-strength values even exceeded those of Grade 2. Therefore, the fractures occurred in Grade 2 were not from the weld area.

In the case of room temperature forming, a slight increase in elongation was observed generally on the Grade-2 side of the weldments due to the higher ductility of Grade 2. As a result of the forming process at 500 °C, it was observed that the weld seam shifted from the centre to the Grade-5 side by 14.6 mm. At 850 °C, the deformation occurred towards the Grade-2 side, and the weld seam deviated from the center by 7.3 mm. This is attributed to the fact that Grade 2 and Grade 5 undergo recrystallization at different temperatures, leading to changes in their ductility at these temperatures.

By increasing the forming start temperature from room temperature up to 500 °C and 850 °C, different average hardness values were obtained on the Grade-2 and Grade-5 sides of the weldments. While a significant decrease in hardness was observed with the increase in temperature on the Grade-5 side, the lowest hardness values were recorded at 500 °C on the Grade-2 side.

The springback behaviour of the Ti-TWBs was also affected by the forming start temperature and dimensional accuracy improved with increasing temperature on both the Grade-2 and Grade-5 sides. The springback angles of the formed weldments exhibited a maximum improvement of 40 % on the Grade-2 side and 37 % on the Grade-5 side at 850 °C.

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