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Original Research Article

EBW titanium sheets as material for drawn parts

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ABSTRACT

The growing demand for high strength, lightweight and corrosion-resistant drawn parts has created increasing interest in the use of titanium and its alloys. Additional benefits may result from the use of tailor-welded blanks, allowing for significant savings in material, and the possibility of applying higher strength sheets exactly where needed. When forming welded blanks, it is necessary to overcome many technological barriers which are not reflected in technical literature. Therefore, some prior experience in numerical simulations is needed before embarking on further studies of welded blanks formability. For this purpose, it is necessary to determine the mechanical parameters of the base materials, as well as the fusion and heat-affected zones.

The paper is devoted to the analysis of an electron beam welded joint made of commercially pure titanium Grade 2 and titanium alloy Grade 5. Light microscopy was used for examination of the joint microstructure and determination of the size of the specific joint zones. The mechanical parameters of the base materials were specified in a tensile test, while the material properties of the fusion and heat-affected zones were estimated on the basis of the relationship between the material hardness and strength assuming that the yield stress is directly proportional to the material hardness. To do this, a scratch test and microhardness measurements (using small load) were carried out. The obtained results allow for improvement to the numerical model of sheet-metal forming welded blanks and consequently, it will allow for better agreement between the numerical and empirical results.

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1. Introduction

Titanium and its alloys are exceptional structural materials due to their low specific gravity, high mechanical strength and good corrosion resistance to many aggressive atmospheres. Therefore titanium is used wherever low weight and high strength constructions are essential, i.e. whenever common structural materials such as aluminium and steel fail.

A growing demand for titanium products, including drawn parts, is especially observed in medicine and the ground or air vehicle industry, as discussed in Boyer and Briggs [1], Faller and Froes [2], Jones et al. [3], Kosaka and Fox [4], Li et al. [5], Niinomi et al. [6], Rack and Qaz [7] and Yamada [8]. Drawn

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parts considerably reduce the construction weight and simultaneously provide sufficient strength. Hyrcza-Michalska et al. [9], Lai and Chan [10], Lai et al. [11], Sinke et al. [12,13] and Zadpoor et al. [14] have pointed out that additional benefits may result from the use of so-called tailor-welded blanks. Such blanks are made from individual sheets of different grade, thickness or coating which are generally joined together by laser welding [15–19]. Tailor-welded blanks (TWB) technology ensures that the finished element features the right material in the right place, i.e. thicker or higher-strength materials are used in highly stressed areas, while thinner sheets or softer deep-drawing grades are used in other areas. Presently, this technology is widely used in the automotive industry due to:

1. total weight reduction, which directly transforms into a decrease in fuel consumption and CO_2 emission
2. cost reduction – expensive materials are only used where they are needed
3. improvement in corrosion behaviour thanks to elimination of overlapping blanks.

Although the applications of tailor-welded blanks technology in the aircraft industry are almost absent, it seems that the aircraft industry can also benefit from this technology as developed in the automotive industry. Zadpoor et al. [14] stated that the technological barriers preventing the aircraft industry from using the tailor-welded blank technology result from the low production series, specific alloys, and joining methods used in this industry.

The joining method plays an essential role in the production of tailor-welded blanks. To date, laser welding has been the main method. It was developed in 1985 by the Thyssen company in cooperation with Rofin-Sinar for production of the underbody of the Audi 100. Since that time TWB technology has developed almost simultaneously in Europe, Japan and the U.S. Although laser welding provides a very precise weld, in the work, electron beam welding (EBW) is analysed, as reported in Yunlian et al. [20] increased titanium reactivity with atmospheric elements at high temperatures necessitates additional precautions to shield the molten weld pool. EBW permits the generation of a keyhole that effectively concentrates the energy input into a small area, there is good potential to join titanium alloys since the microstructural changes are confined to the weld region and a narrow heat affected zone [21–25].

The main aim of this work is to analyse titanium welded blanks as a material used for drawn parts. Adamus [26,27], Adamus and Lacki [28,29], Ceretti et al. [30], Lacki et al. [25], Motyka and Sieniawski [31], and Yang et al. [32] discussed that forming titanium sheets is not an easy task, especially titanium alloys which are characterised as being poorly drawable at ambient temperature. The tailor-welded blank concept is even more difficult. The weld poses an additional obstacle in forming. Adamus et al. [35], Akman et al. [15], Lacki et al. [25], Lai et al. [33,11,10], Li et al. [16], Winowiecka et al. [34] and Zadpoor et al. [14] pointed out that it limits the ductility of TWBs. Therefore, new techniques are needed to design welded blank applications. Numerical simulations are a very useful tool in understanding the phenomenon appearing in the forming process and optimising the structural performance of the part. Although numerical modelling is a powerful economic method of visualising the process course (e.g. change in stress, strain and thickness, prediction of forming failure), it needs some actual data. Proper determination of the mechanical properties for the weld material is one of the key factors having impact on the results of the numerical simulations.

2. Goal and scope of study

The main aim of the study is to provide some mechanical properties of the different weld zones such as fusion and heat-affected zones (HAZ) which are important in the FEM models of welded blanks.

Welded blanks made of:

- commercially pure titanium Grade 2 (% chemical composition: C – 0.014, Fe – 0.08, O – 0.11, N – 0.005, H – 22/32 (ppm), Ti– residue),
- titanium alloy Grade 5 (Ti6Al4V) (% chemical composition: Al – 6.3, V – 4.1, C – 0.003, Fe – 0.2, Y – <0.006, O – 0.02, N – 0.006, H – 0.001, Ti – residue)

were analysed. The thickness of both sheets was 0.8 mm. Sheets with the dimensions 125 mm × 150 mm were joined together by electron beam welding. The following EBW parameters were used: welding current $I = 4.6$ mA, voltage $U = 120$ kV, welding speed $v = 20$ mm/s. The electron beam was focused on the material surface.

The samples for the tensile test were cut out of the welded sheets by abrasive waterjet cutting.

The characteristics of the base materials were determined on the basis of the tensile test, while the scratch test, microhardness measurements and metallographic observations were used for the material of the fusion and heat-affected zones.

3. Test results

3.1. *Tensile test*

Miniature test specimens were used in the tensile test as shown in Fig. 1. From the welded sample which includes both the weld and the base metals the metallographic specimens were prepared to further analyse the joint microstructure,

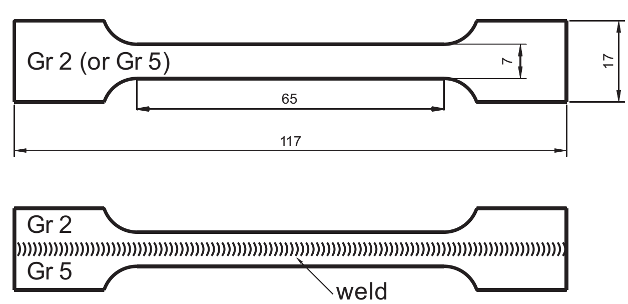

Fig. 1 – Tensile specimens.

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Table 1 – Properties of base materials.

Property	Base material	
	Grade 5	Grade 2
Tensile strength R_m [MPa]	906.4	343.6
Yield strength $R_{0,2}$ [MPa]	892.2	267.7
Young's modulus E [GPa]	110	110
Poisson's ratio ν [–]	0.37	0.37
Strain hardening index n [–]	0.04	0.15
Strength coefficient K [MPa]	1241	743

measure microhardness and scratch test. Table 1 shows the tensile test results for the base materials.

3.2. *Microhardness measurements*

The results of microhardness measurements are presented in Fig. 2. The microhardness graph has been superimposed on the joint microstructure.

Analysis of the microhardness results shows that 5 different zones can be distinguished. They are as follows:

- titanium alloy Grade 5 (M1) with mean hardness value ~357 $HV_{0.02}$
- heat affected zone in Grade 5 (HAZ1) with mean hardness value ~249 $HV_{0.02}$
- fusion zone (FZ) with mean hardness value ~283 $HV_{0.02}$
- heat affected zone in Grade 2 (HAZ2) with mean hardness value ~160 $HV_{0.02}$
- commercially pure titanium Grade 2 (M2) with mean hardness value ~177 $HV_{0.02}$.

3.3. *Scratch test*

Due to the fact that microhardness measurements are carried out for randomly selected points, a scratch test has been chosen as a baseline study to determine the mechanical properties, i.e. yield and tensile strength of the FZ and HAZ materials. The scratch test is generally dedicated for characterising the adhesion of thin films and coatings to the surface. Application of this technique involves generating a

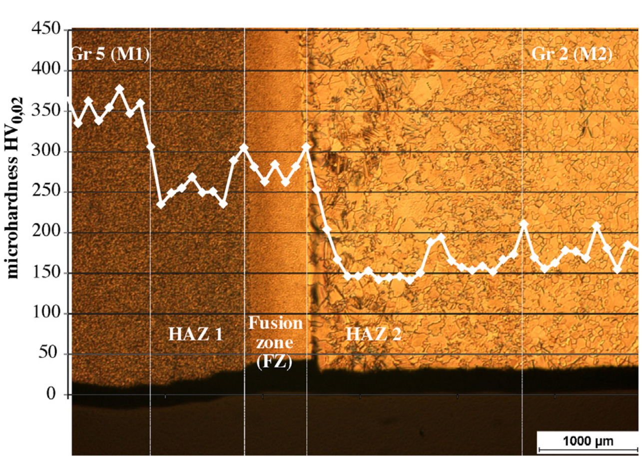

Fig. 2 – Specific material zones distinguished on basis of hardness measurements and metallographic observations.

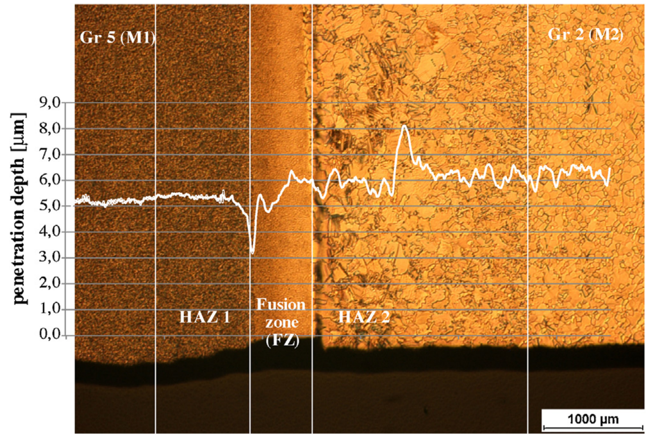

Fig. 3 – Specific material zones distinguished on basis of scratch test and metallographic observations.

Table 2 – Yield and tensile strength of the fusion zone and the heat affected zones.

Property	Material		
	HAZ1 (in Grade 5)	FZ (fusion zone)	HAZ2 (in Grade 2)
Yield strength [MPa]	795.29	768.37	547.65
Tensile strength [MPa]	819.05	794.79	595.88

controlled scratch with a sharp tip on the selected area. A Rockwell diamond indenter with a radius of 200 μm was drawn across the analysed surface under the constant load of 10 N, with the speed of 8.6 mm/min.

The yield and tensile strength of the material in specific weld zones was estimated based on the relationship between the penetration depth, which is a measure of hardness, and material strength assuming that the yield stress is in direct proportion to the material hardness. The scratch test results are presented in Fig. 3. The penetration depth has been superimposed on the joint microstructure.

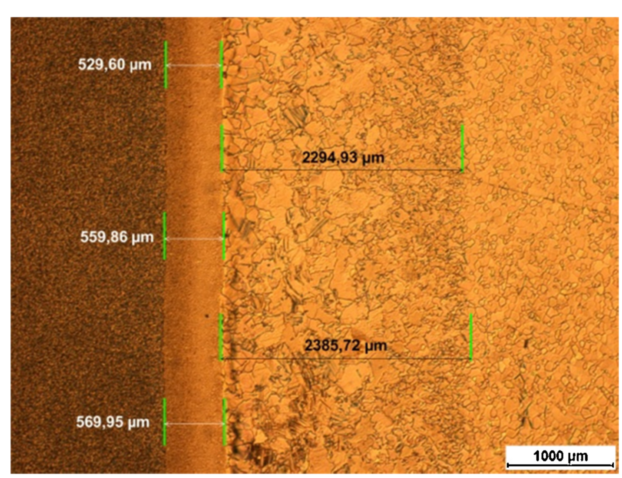

Fig. 4 – Microstructure of the EBW joint between Gr 5 and Gr 2.

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Fig. 5 – Microstructure of Grade 5 titanium alloy.

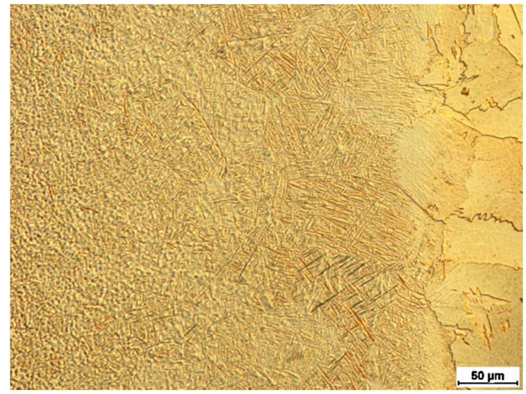

Fig. 7 – Microstructure of the melting zone and HAZ in Grade 2 (right).

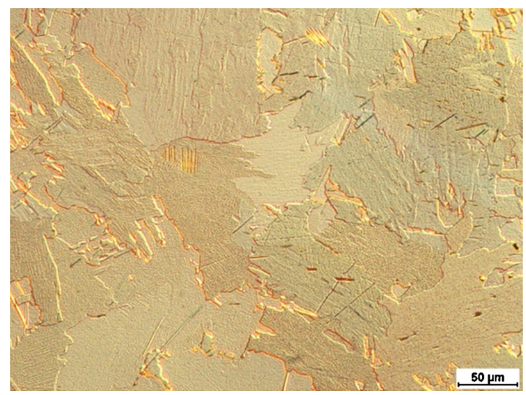

Fig. 8 – Microstructure of HAZ in Grade 2.

The distinguished material zones have mean penetration depth as follows:

- base material – Grade 5 (M1): 5.12 µm,
- heat affected zone in Grade 5 (HAZ1): 5.30 µm,
- fusion zone (FZ): 5.35 µm,
- heat affected zone in Grade 2 (HAZ2): 5.76 µm,
- base material – Grade 2 (M2): 6.28 µm.

On the basis of the base material tensile strength and penetration depth, the yield strength and tensile strength for the fusion and heat affected zones were estimated, as given in Table 2. These data are then used in the numerical calculations of the sheet metal forming processes of the welded blanks.

3.4. *Metallographic examinations*

The metallographic examinations show nonuniformity in the weld microstructure (Fig. 4).

The following zones can be distinguished from the left: base material Grade 5, heat affected zone in Grade 5, fusion zone, heat affected zone in Grade 2 and base material Grade 2.As seen from Fig. 4, the microstructure changes include an area of about 4 mm in width. A large HAZ appears at the side of Grade 2, its width is ~2282 µm. The width of fusion zone is ~553 µm, while the width of HAZ in Grade 5, which is hardly visible in Fig. 4, is about 1000 µm.

The microstructures of the specific zones of the EBW joint starting from titanium alloy Ti6Al4V through HAZ in Grade 5, melting zone, HAZ in Grade 2 to the Grade 2 base metal are sequentially shown in Figs. 5–9.

The microstructure of the Grade 5 (Ti–6Al–4V) alloy contains a fine-grained globular α phase separated by a β phase precipitated along the grain boundaries (Fig. 5). The alloy microstructure slightly changes in HAZ–grain refinement

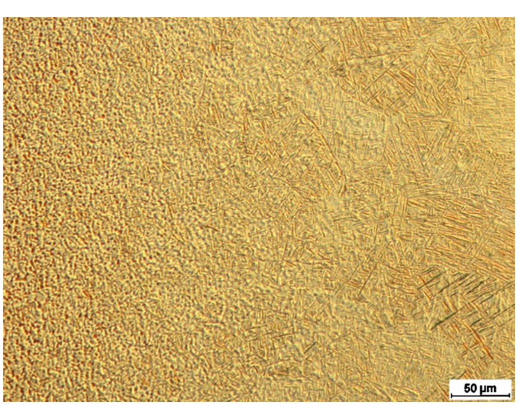

Fig. 6 – Microstructure of HAZ in Grade 5 (left) gradually undergoes into the melting zone.

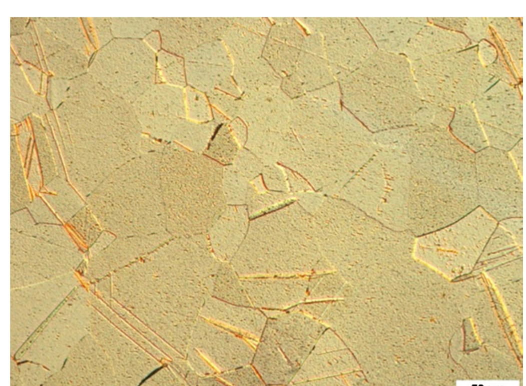

Fig. 9 – Microstructure of Grade 2.

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is observed (Fig. 6). The transition zone between HAZ in Grade 5 and the fusion zone is smooth in contrast to the fusion zone/HAZ in the Grade 2 interface (Fig. 7). A martensitic microstructure was observed in the melting zone (Fig. 7) – typical for $\alpha + \beta$ titanium alloys. The microscopic observations of HAZ in Grade 2 revealed coarse α grains having irregular shapes (Fig. 8) which differ from the native material microstructure (Fig. 9) composed of recrystallized α grains containing lenticular twins.

4. Discussion

In order to foresee material behaviour during sheet-metal forming correctly, it is necessary to create a numerical model of the forming process as realistic as possible. Failure to take account of material properties of HAZ and FZ could be too much simplification. Especially that in the area between HAZ in Grade 5 and fusion zone there is a sudden decrease in penetration depth (see Fig. 3), which means significant drop in plasticity. To compare the results of the performed tests line charts of the microhardness and penetration depth were plotted on the joint microstructure (see Figs. 2 and 3 respectively). The analysis of these two figures shows some agreement between the carried out tests and metallographic observations. At least 5 areas with different mechanical properties could be distinguished. It involves nonuniformity in the material flow in the further forming of welded blanks. Therefore assessment of the yield and tensile strength for these zones is important. Yield and tensile strength of HAZ and fusion zone were evaluated on the basis of scratch test due to the fact that microhardness measurements are performed for randomly selected points. It is also a reason of discrepancy between the microhardness and scratch test results. The microhardness measurements were an additional source of information. Microhardness changes in the weld area result from microstructural changes. Diffusion of alloying elements from Grade 5 into Grade 2 causes both a significant increase in microhardness of HAZ in Grade 2 near the fusion zone and a decrease in microhardness of HAZ in Grade 5. Creation of martensite due to high cooling rate could be another reason for drop in microhardness of HAZ in Grade 5. Unlike steel, titanium alloys became more ductile after quenching.

5. Conclusions

1. All the experimental studies have shown that there are at least 5 areas with different mechanical properties in EBW titanium blanks. It in turn involves nonuniformity in material flow during sheet-metal forming processes. Therefore, a numerical model of sheet-metal forming should take into consideration these zones. It allows for increasing the accuracy of numerical simulation results.
2. In order to confirm the reason why microhardness changes in HAZ and FZ in relations to the base materials the linear distribution of alloying elements content should be performed.
3. Further studies will be focused on searching mathematical correlation between titanium material hardness and its mechanical properties.

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