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EVALUATION OF DRAWABILITY OF TITANIUM WELDED SHEETS

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In the paper experimental and numerical results of sheet-metal forming of titanium welded blanks are presented. Commercially pure titanium Grade 2 (Gr 2) and Ti6Al4V titanium alloy (Gr 5) are tested. Forming the spherical cups from the welded Gr 2 || Gr 5 blanks, and uniform Gr 2 and Gr 5 blanks is analysed. Numerical simulations were performed using the PamStamp 2G v2012 program based on the finite element method (FEM). Additionally, drawability tests using the tool consisting of die, hemispherical punch and blank-holder were carried out. Thickness changes and plastic strain distributions in the deformed material are analysed. The obtained results show some difficulties occurring during forming of the welded blanks made of titanium sheets at the same thicknesses but at different grades. It provide important information about the process course and might be useful in design and optimization of the sheet-titanium forming process.

Keywords: sheet-metal forming, titanium sheet, welded blanks, FEM modelling

W artykule przedstawiono wyniki badań doświadczalnych oraz symulacji numerycznych procesu tłoczenia spawanych wsadów typu Tailor-Welded Blanks wykonanych z blach tytanowych. Przeprowadzono analizę procesu kształtowania czaszy kulistej z wsadu spawanego oraz z materiałów jednorodnych: Grade 2 i Grade 5. Obliczenia numeryczne przeprowadzono przy użyciu programu PamStamp. Dodatkowo przeprowadzono próby tłoczności (próby wybrzuszania stemplem sferycznym) przy zastosowaniu specjalnie przygotowanego narzędzia składającego się z matrycy, półkulistego stempla oraz pierścienia dociskowego. Dokonano oceny rozkładów odkształceń plastycznych w materiale wytłoczek oraz zmian grubości ścianek wytłoczek. Uzyskane wyniki wskazują na trudności występujące podczas kształtowania tytanowych blach spawanych oraz dostarczają informacji o przebiegu tego typu procesu. Tym samym uzyskane wyniki mogą być przydatne na etapie projektowania i optymalizacji procesów tłoczenia.

1. Introduction

The increase in demand for shell parts, especially from automotive and aircraft industry, leads to attempts to evaluate forming possibilities of hard-to-deform sheets, such as alpha and beta titanium alloys or tailor-welded blanks (TWB). Application of TWB's allow for reduction of both product weight and manufacturing costs due to limitation of material consumption and number of required forming operations, and consequently decrease in demand for tools. It is estimated that application of TWB can reduce the number of required parts to 66% and reduce the weight by half [1-6].

Good drawability characterises Gr 2 titanium sheets however the drawn-parts made of such sheets have low strength. Unlike Gr 2 sheets, Gr 5 (Ti6Al4V) titanium sheets have high mechanical properties (yield strength and ultimate tensile strength) and thus low ability to deform plastically. So their application in stamping processes is limited [7-9].

In the case of forming process of welded blanks the weld causes some changes in material deformation scheme compared to deformations that occur during forming of the uniform material. It results from the fact that generally the weld has lower ability to plastically deform than the base material, and also due to weld dislocation. Direction and magnitude of the weld dislocation depend on the difference in thickness and mechanical properties between welded materials [1, 6, 10].

In order to evaluate suitability of welded blanks for the sheet-metal forming processes, it is necessary to carry out some studies, including numerical simulations of welding and stamping processes, that will allow for prediction of sheet behaviour in consecutive stages of the forming process [5-15].

According to [9, 16] semi-flexible forming is one of the methods improving formability of the hard to deform at ambient temperature sheets. Such forming methods allow for obtaining the deeper draw parts.

2. Goal and scope of the work

Evaluation of the welded blanks drawability in traditional forming processes using numerical simulation and experimental studies is the goal of the work.

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The numerical simulations of sheet-titanium forming of welded blanks were performed. The numerical calculations for three-dimensional model using the PamStamp program were carried out [17]. The elastic-plastic material model using anisotropic plasticity (Hill'48 yield criterion) was assumed. Forming of the spherical cups from the welded blanks, and uniform Gr 2 and Gr 5 sheets was analysed. The mechanical characteristics of the sheets, weld and heat affected zones (HAZ) were determined based on the experimental tests. Additionally, drawability tests were carried out using the tool consisting of the die, hemispherical punch and blank-holder. Plastic strain distribution and thickness changes in the drawn-part material were determined.

3. Experimental study

The experimental studies were carried out in order to determine mechanical properties of the analysed materials. The samples made of commercially pure titanium Gr 2, titanium alloy Gr 5 and welded materials: Gr 2 || Gr 5 were tested. Mechanical properties, which are necessary for the numerical calculations, were determined in a tensile test and a scratch test. During the scratch test penetration depth of diamond indenter was recorded as a measure of the material hardness. Drawability test of the analysed materials was carried out using the tool consisting of the die with diameter 30 mm and fillet radius of 5 mm, the hemispherical punch with a diameter of 28 mm and the blank-holder with an inner diameter of 40 mm. The blank diameter was 60 mm and its thickness was 0.8 mm. The welded blanks were prepared using electron beam welding. The test results, which are given in Table 1, allowed for developing a material model for numerical simulations of the forming process. Hollomon's equation defining a relationship between flow stress and plastic strain

$$\sigma = \mathrm{K} \cdot \varepsilon^n$$

was used to define strain hardening of the material. K is a material constant and n is a strain-hardening exponent.

TABLE 1

Material properties used in definition of the material model: E – Young's modulus, R_e – yield point, ν – Poisson ratio, ρ – specific gravity, K – material constant, n – strain-hardening exponent

Parameter	E GPa	R_e GPa	ν –	ρ kg/m^3	K GPa	n –
Grade 2	105	0.236	0.37	4500	0.465	0.125
Grade 2 HAZ	105	0.368	0.37	4500	0.510	0.049
Weld	110	0.375	0.37	4500	0.672	0.078
Grade 5 HAZ	114	0.747	0.37	4400	0.921	0.030
Grade 5	114	0.964	0.37	4400	1.172	0.039

The equations of work-hardening curves for Grade 2 and Grade 5 titanium were plotted on the basis of the tensile test, while the equations for the specific heat affected zones were determined using the indirect method i.e. on the base of penetration depth measurement in scratch test. Work-hardening curves for the analysed materials are presented in Fig. 1.

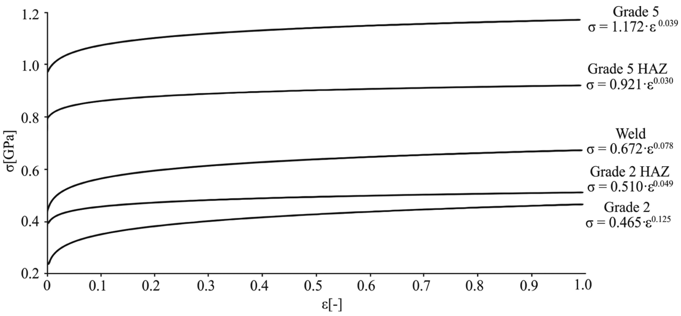

Fig. 1. Work-hardening curves for the analysed materials

The test results of the stamping process for the spherical cup made of Gr 2 titanium sheet using a holding-down force of 1.5 kN are shown in Fig. 2a. The maximal stamping force during the test was 4.1 kN. The prestamped flat blank was completely converted into the drawn-part without any marks of fracture.

The numerical calculation results of the stamping process for the spherical cup made of Gr 5 sheet using holding-down force of 1.5 kN are shown in Fig. 2b. The first cracks were noticed for the drawn-in of 8.9 mm. Stamping force at fracture moment was about 2.8 kN.

The numerical calculation results of stamping process for the spherical cup made of welded blank Gr 2 || Gr 5 using holding-down force of 1.5 kN are shown in Fig. 2c. Stamping force at fracture moment was about 1.87÷1.95 kN .The first cracks were observed for the drawn-in of 7.4÷8.0 mm, near the heat-affected zone in Gr 2 sheet. Additionally, the weld dislocation in the direction of Gr 5 sheet was observed.

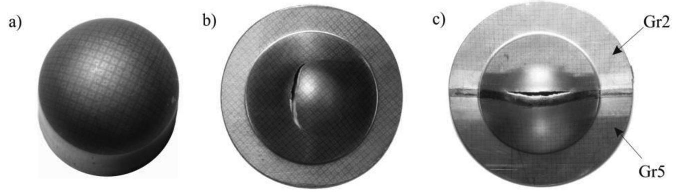

Fig. 2. Test results of the stamping process: a) uniform Gr 2 sheet, b) uniform Gr 5 sheet, c) welded blank Gr 2 || Gr 5

4. Numerical study

4.1. Numerical model

A numerical model of the tool was elaborated on the basis of the real tool. The tool geometry was designed so as to be able to produce real parts with a shape of spherical cup with diameter of 28 mm. The rigid shell model of the tool, which is shown in Fig. 3, was prepared using the Catia System v.5, and then it was imported into the PamStamp program as the individual tool parts. 4-node shell elements were automatically generated on the individual tool parts and the blank. The boundary conditions are assigned to the individual tool parts. All degrees of freedom are taken away from the die. The punch and the blank-holder can move only in Z direction. A displacement is applied to the punch and the blank-holder. A holding-down force is applied only to the blank-holder. The blank has all the degrees of freedom. Uniform specimens are defined as a disc with 60 mm diameter. In the welded blank

5 zones are distinguished: the weld zone, two heat affected zones, located symmetrically on both sides of the weld and two zones representing the base materials (Fig. 4). Geometric parameters of these zones were determined based on the experimental measurements.

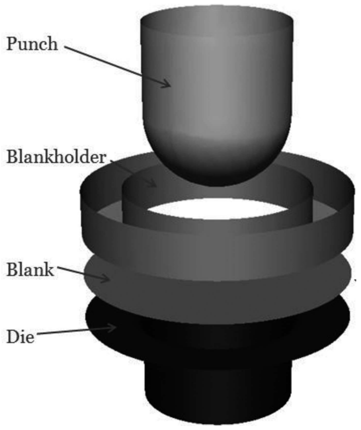

Fig. 3. Rigid shell model of the tool

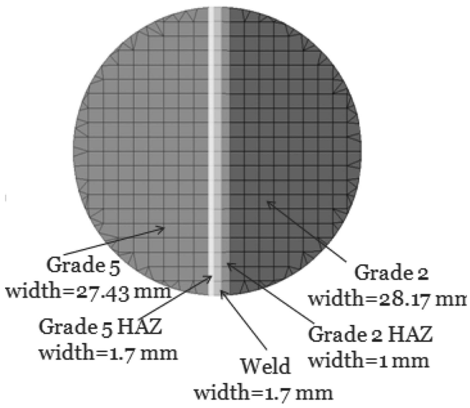

Fig. 4. Dimension of the zones of welded blank

Different frictional conditions and holding-down forces were considered in the numerical simulations. The holding-down force ranges from 1.0 to 3.0 kN with increments of 0.5 kN. A contact interaction between the tool surface and the blank plays an important role in sheet-metal forming thus different friction coefficients were analysed. Friction coefficient μ =0.1 was assumed for lubricated surfaces while μ =0.3 for unlubricated surfaces. The different configurations of frictional conditions for the contact surfaces: ”deformed material – blank-holder”, ”deformed material – die” and ”deformed material – punch” were considered. The numerical simulations included: full lubrication of the working surfaces – μ =0.1, dry conditions (with no lubrication) - μ =0.3, diversified frictional conditions (high friction coefficient – μ =0.3 – for the contact surface between the punch and the deformed material, and low friction coefficient – μ =0.1 – for the other frictional contact surfaces), and lubrication of the selected areas of the blank – μ =0.1. The drawn-parts were analysed using different draw-in depending on the kind of the deformed material.

4.2. Numerical calculation results

The numerical calculation results of the stamping process for the spherical cup made of Gr 2 sheet in dry condition are shown in Fig. 5. A comparison between plastic strains in the drawn-part and forming limit curve (FLC) is presented. Similarly to the experimental test the properly shaped drawn-part without any cracks was obtained. The cup height was 27.2 mm.

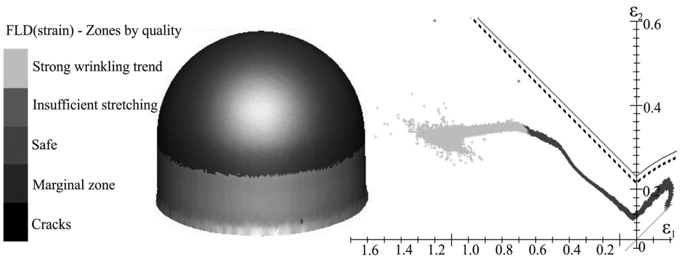

Fig. 5. Strain distribution in the drawn-part made of Gr 2 sheet

Because the other materials crack earlier the forming process was analysed for draw-in of 10 mm. It allows for comparison between the strain and stress states in all drawn-parts before the onset of fracture or wrinkling. The analysis of the influence of holding-down force on the deformation course showed that an increase in holding-down force causes the growth in plastic strains and material thinning.

The frictional conditions also substantially affect the forming process. The largest plastic strains and material thinning occur for forming process with no lubrication (μ =0.3). While the smallest plastic strains and the smallest thinning are observed for the diverse frictional conditions: μ =0.3 for the contact surface: “punch – blank”, and μ =0.1 for the contact surfaces: “die – blank” and “blank – blank-holder. The numerical calculation results are shown in Fig. 6.

In the case of forming process of the uniform Gr 2 blank the homogenous and circular plastic strain distribution is observed, and maximal plastic strains appear on a pole of the drawn-part.

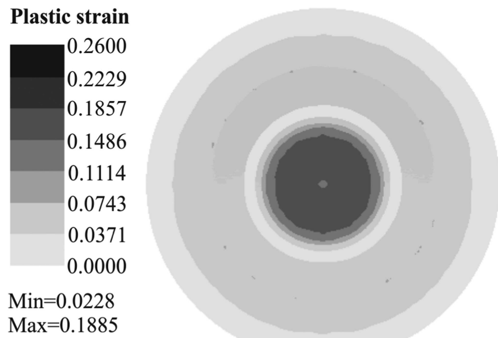

Fig. 6. Plastic strain distribution in the drawn-part made of Gr 2 sheet for the diversified frictional conditions: “punch – blank” μ =0.3, “die – blank” and “blank – blank-holder” μ =0.1, and holding-down force of 1.5 kN

The numerical calculation results of the forming process for the spherical cup made of Gr 5 sheet without lubrication is shown in Fig. 7. Plastic strain distribution and forming limit curve are presented. The numerical calculation results for the same frictional conditions as for Gr 2 sheet show cracks at the punch draw-in of 9.0 mm.

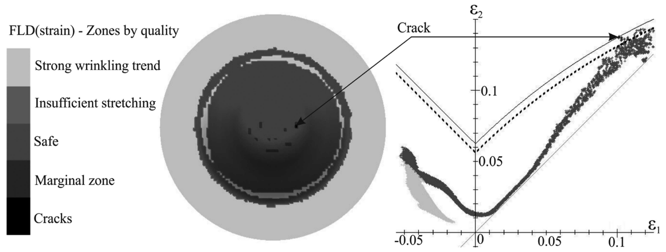

Fig. 7. Strain distribution in the drawn-part made of Gr 5 sheet; excessive strains are marked in the crack zone

The numerical simulation results show that crack moment largely depends on the frictional conditions and value of the holding-down force. When holding-down force is low – 1.0 kN – cracks are not observed until draw-in reaches 10 mm, but simultaneously high risk of flange wrinkling is expected.

The smallest cup depth without crack was obtained for forming with no lubrication while the largest cup depth was obtained for the diversified frictional conditions. The numerical calculation results are shown in Fig. 8. Homogenous and circular plastic strain distribution is observed when the uniform Gr 5 blank is stamped. This distribution is similar to the numerical results obtained for uniform Gr 2 sheet although the plastic strains are 30% higher.

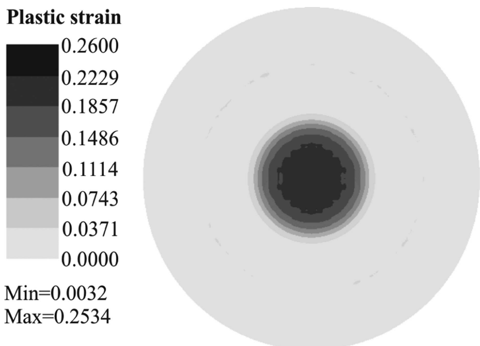

Fig. 8. Strain distribution in the drawn-part made of Gr 2 sheet for forming in dry condition at the onset of crack; holding-down force of 1.5 kN

The numerical calculation results of the forming process of the spherical cup made of welded blank Gr 2 || Gr 5 are shown in Fig. 9. The plastic strain distribution in the drawn-part and forming limit curve are presented. The numerical calculation results, for the same frictional conditions, show cracks when the punch draw-in is 9.0 mm.

The numerical simulation of the stamping process of Gr 2 || Gr 5 blank was realized for the punch draw-in value of up to 10 mm. The plastic strain distribution for the following frictional conditions: "punch – blank" μ =0.3, "die – blank" and "blank – blank-holder" μ =0.1, and holding-down force of 1.5 kN is shown in Fig. 10. Small plastic strains in Gr 5 sheet and high plastic strains in the heat-affected zone in Gr 2 sheet are observed.

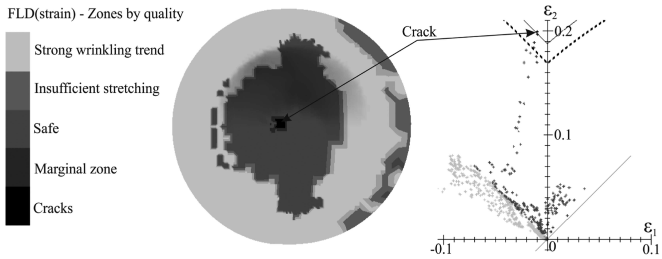

Fig. 9. Plastic strain distribution in the drawn-part made of welded blank Gr 2 || Gr 5; excessive strains are marked in the crack zone

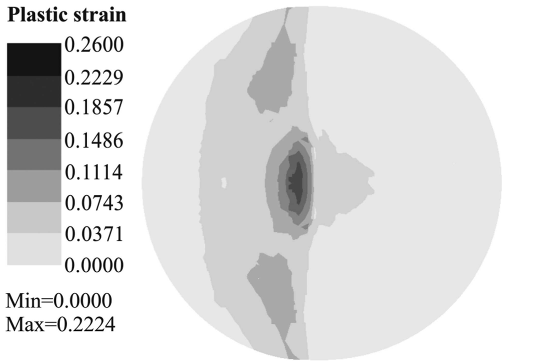

Fig. 10. Plastic strain distribution in the drawn-part made of the welded blank Gr 2 || Gr 5 for the following frictional conditions: "punch – blank" μ =0.3, "die – blank" and "blank – blank-holder" μ =0.1, holding-down force at the onset of crack is 1.5 kN

The detailed numerical simulation results for all analysed cases are presented in TABLES 2 and 3. A comparison of the numerical simulation results for the different values of holding-down force and friction condition is presented in TABLE 2. Thinning and plastic strains at the onset of crack are similar for all considered cases, but the cup depth decreases with the increase in holding-down force. For the holding-down force of 3kN it is possible to obtain the cup depth of only 6.6 mm. The largest cup depth is expected for the holding-down forces of 1.0 and 1.5 kN.

TABLE 2

A comparison of the forming results for the welded blanks in diverse frictional conditions: "punch – blank" μ =0.3; "die – blank" and "blank – blank-holder" μ =0.1 using different holding force at the onset of fracture

Holding-down force [kN]	1	1.5	2	2.5	3
Thinning [mm]	0.1767	0.1720	0.1728	0.1732)	0.1703
Maximal plastic strain [-]	0.2339	0.2224	0.2226	0.2220	0.2167
Cup depth at the onset of crack [mm]	7.5	7.5	7.3	7.0	6.6

TABLE 3 presents the comparison of the analysed forming parameters for the holding-down force of 1.5 kN and different frictional conditions: (1) lubrication only for Gr 2 sheet μ =0.1, (2) lubrication only for Gr 5 sheet μ =0.1, (3) μ =0.1 for "punch – blank", and μ =0.3 for "die – blank" and "blank – blank-holder", (4) μ =0.3 for "punch – blank", and μ =0.1 for "die – blank" and "blank – blank-holder", (5) lubrication of all tools, (6) without lubrication. The smallest cup depth of 5.1 mm was obtained for dry conditions (no lubrication), while the largest cup depth was obtained for frictional configuration (4). For all considered configurations maximal value of plastic strains and material thinning at the onset of crack is similar.

TABLE 3
A comparison of some calculation results for optimal holding-down force of 1.5 kN

Configuration	1	2	3	4	5	6
Thinning [mm]	0.1770	0.1770	0.1761	0 .1720	0.1732	0.1746
Maximal plastic strain[-]	0.2222	0.2239	0.2212	0.2224	0.2165	0.2190
Cup depth at the onset of crack [mm]	5.6	5.5	5.3	7.5	5.4	5.1

5. Conclusions

The numerical calculations showed that the cup depth strongly depends on the value of holding-down force and frictional conditions between the tool and deformed material. Holding-down force equal to 1kN is insufficient for forming the uniform Gr 5 blank and welded blank Gr 2 || Gr 5 - significant wrinkling of the flange area in Gr 5 sheet is observed. Crack always occurs near heat affected zone in Gr 2 sheet. Moreover a significant dislocation of the weld is observed as a result of larger plastic strains in Gr 2 sheet.

For all considered cases the increase in holding-down force causes growth in plastic strains, significant thinning of the cup walls and decrease in the cup depth at the crack moment.

During design of the welded blanks forming process it is necessary to take into consideration that too small holding-down force causes wrinkling in material with less drawability, while too large holding-down force causes damage of the material with smaller yield strain. It should be also taken into account that there is the possibility of weld dislocation. The proper selection of the process parameters enables forming of the analysed welded blanks.

Numerical and experimental studies are slightly different. The difference in stamping depth is 9.7%.

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REFERENCES

[1] M. Hyrcza-Michalska, F. Grosman, Arch. Civ. Mech. Eng. **9**, 69 (2009).
[2] J. Sinke, C. Iacono, A.A. Zadpoor, Int.. J Mater. Form **3**, 1, 849 (2010).
[3] E. Schubert, M. Klassen, C. Zerner, C. Walz, G. Seplod, J. Mater. Process. Tech. **115**, 2 (2001).
[4] X.G. Qiu, W.L. Chen, J. Mater. Process. Tech. **187-188**, 128 (2007).
[5] K.V. Babu, R.G. Narayanan, G.S. Kumar, Expert. Syst. Appl. **37**, 7802 (2010).
[6] T. Meinders, A. van den Berg, J. Huetink, J. Mater.Process. Tech. **103**, 65 (2000).
[7] J. Adamus, P. Lacki, M. Motyka, K. Kubiak, in., 12th World Conference on Titanium Ti 2011, China National Convention Center (CNCC), Science Press Beijing, 337 Beijing (2011).
[8] J. Adamus, Key Eng. Mat. **410-411**, 279 (2009).
[9] J. Adamus, P. Lacki, Arch. Metall. Mater. **57**, 1247 (2012).
[10] M. Hyrcza-Michalska, J. Rojek, O. Fruitos, Arch. Civ. Mech. Eng. **10**, 4, 31 (2010).
[11] J. Lisok, A. Piela, Arch. Civ. Mech. Eng. **4**, 333 (2004).
[12] Z. Zimniak, A. Piela, J. Mater. Process. Tech. **106**, 254 (2000).
[13] A. Piela, J. Rojek, Arch. Metall. Mater. **48**, 1, 37 (2003).
[14] A.A. Zadpoor, J. Sinke, R. Benedictus, Key Eng. Mat. **344**, 373 (2007).
[15] P. Lacki, K. Adamus, Comput. Struct. **89**, 977 (2011).
[16] D. Woźniak, M. Głowacki, M. Hojny, T. Pieja, Arch. Metall. Mater. **57**, 4, 1179 (2012).
[17] PamStamp 2G 2011, User's Guide.