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THEORETICAL AND EXPERIMENTAL ANALYSIS OF THE SHEET-TITANIUM FORMING PROCESS

TEORETYCZNO – DOŚWIADCZALNA ANALIZA PROCESU TŁOCZENIA BLACH TYTANOWYCH

In the paper sheet-metal forming process, the essential part of modern industry, which enable us to produce the applied drawpiece e.g. in the aircraft, car or building industry, was discussed. Advantages and disadvantages of application of titanium and its alloys in the drawpieces were presented. The numerical simulation results of the stamping process of CP 2 titanium cylindrical cup were given. Material data needed for the numerical simulation, such as: *Re*, *Rm*, *r*-value, hardening coefficient *n*, forming limit diagram (*FLD*), were determined experimentally. A special attention was paid to the impact of such parameters as: friction coefficient, tool geometry (corner radius of the die and punch) and holding-down force on the strain distribution in the drawpiece. The simulation results were compared with the experimental ones. The numerical simulation was carried out with the ADINA System based on the finite element methods (MES).

Keywords: sheet-metal forming process, titanium, numerical simulation

W artykule omówiono proces tłoczenia blach, jako istotny element nowoczesnego przemysłu, pozwalający na produkcję wytłoczek stosowanych w przemyśle lotniczym, samochodowym, budowlanym itp. Przedstawiono wady i zalety tytanu i jego stopów, jako materiałów stosowanych na elementy tłoczone. Podano wyniki symulacji numerycznej procesu tłoczenia tytanowej (CP2) wytłoczki cylindrycznej. Dane materiałowe takie jak: *Re*, *Rm*, współczynnik anizotropii normalnej *r* i wykładnik umocnienia *n*, krzywa odkształceń granicznych *KOG*, itp. niezbędne do symulacji numerycznej wyznaczono doświadczalnie. Szczególną uwagę zwrócono na wpływ takich parametrów jak współczynnik tarcia, geometria narzędzi (promienie zaokrąglenia stempla i matrycy), siła docisku itp. na rozkład odkształceń w wytłoczce. Wyniki symulacji numerycznej porównano z wynikami eksperymentalnymi. Symulację numeryczną przeprowadzono w oparciu o program ADINA System, oparty na metodzie elementów skończonych (MES).

1. Introduction

Sheet-metal forming processes are the fundamental part of modern industry. They allow for obtaining near net-shape shell products which do not require further processing. Quality of the drawpieces largely depends on the material drawability, tool geometry (corner radius of the punch and die) and frictional conditions. Most of the problems occurring during sheet-metal forming processes result from low drawability and poor tribological properties of the deformed material [1,2]. The majority of titanium sheets have such properties. During sheet-titanium forming processes it is necessary to overcome many difficulties which are not described in professional literature sufficiently. Therefore, the Author undertook the task of analysing the stamping process of titanium cylindrical cup.

2. Advantages and disadvantages of application of titanium and its alloys for the drawpieces

Production and processing of titanium on a commercial scale counts barely 60 years while titanium was isolated more than 200 years. In order to satisfy clients' requirements many material grades based on titanium have been created. Generally they can be divided into two groups: commercially pure titanium and titanium alloys.

Titanium drawpieces are mainly made of pure titanium, especially CP1 and CP2, because of their good formability in the ambient temperature. Unfortunately, due to low mechanical strength the drawpieces made of pure titanium are used only for the cases of electronic equipment, cameras, watches, roofing etc. When high strength is required titanium alloys (e.g. Ti6Al4V) are

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used. Titanium alloys have much better mechanical properties but also poorer drawability in the ambient temperature, which makes traditional forming by rigid tools i.e. punch and die impossible. Poor drawability of titanium alloys limits their application to blanking and restriking elements. In order to facilitate forming of titanium alloys processing in higher temperatures (more than 500°C) can be used. However, high titanium susceptibility to absorb oxygen, nitrogen and hydrogen causes that all processes in higher temperatures must be carried out with protective atmosphere or vacuum [3,4]. Gas absorption causes structural changes, hardening of the metallic base or even brittle cracking.

The main factor preventing the widespread use of titanium is its high price. High production costs and the fact that titanium was a strategic resource for many years are the factors behind low number of works in the range of metal forming processes, especially sheet-titanium forming processes.

Despite the aforementioned disadvantageous titanium has also a number of virtues. Firstly, titanium has a low density ranging from 4,43 to 4,85g/cm^3. Secondly, titanium, especially its alloys, has high mechanical strength ranging from R_m ≈240 MPa for CP1 to about 1750 MPa for the heat treated β titanium alloys [5]. A combination of low density and high mechanical strength causes that titanium alloys exceed in that respect nearly all metallic materials. Therefore, they are used everywhere where the construction weight and its strength are crucial (aircraft and aerospace industry, sport equipment, medicine). Thirdly, titanium alloys have Young's modulus two times lower than steel, so they are the excellent material for springs [6,7,8]. Fourthly, titanium has excellent corrosion resistance. Natural, thin (3-7nm) but stable protective oxygen layer (mainly TiO_2) makes titanium resistant to many atmospheric factors, sea water and different chemicals [9,10,11]. Additionally, titanium and its alloys have good biocompability so they are well suited for different medical implants and production of jewellery, glasses and watches.

3. Aim and range of tests

The numerical analysis of sheet-titanium forming process was performed in this work. The simulation was carried out with the ADINA System v.8.3 based on the finite element method [12]. The influence of friction, holding-down force and geometry on strain distribution in the drawpiece was analysed. The results of computer simulation were compared with experimental ones. The data necessary to perform numerical analysis such as: yield stress R_e, tensile strength R_m, hardening coefficient n, r-value, FLD or frictional coefficient μ were determined empirically. In order to determine the mechanical properties a tensile test was applied according to [13]. The frictional coefficient was obtained using so called "strip-drawing" test described in detail in [14]. The numerical analysis was performed for CP2 titanium sheet containing apart from Ti small impurities of: C – 0,014%, Fe – 0,08%, O – 0,11%, N – 0,005% and H – 22÷23ppm [15]. The analysis was done for axial symmetric – cylindrical cup.

4. The test results

Some test results obtained through the tensile test, which was performed in room temperature, are presented in table 1.

TABLE 1

The mechanical and technological properties of CP2 titanium sheet

material	direction*	$Re_{0,2}$ [MPa]	Rm [MPa]	Elongation A [%]	drawing ratio m_{gr}	strain-hardening coefficient n	material constant C [MPa]
CP2	0°	368	522	37	2,34	0,18	822
	45°	399	486	36		0,15	711
	90°	424	496	14		0,113	726

* sample direction according to the rolling direction of the sheet

Figure 1 presents empirically obtained forming limit diagram (FLD) [14] which can be used during numerical simulation to assess drawpiece design already at the stage of technological process development. According to Figure 1 strain value in the lowest point of curve φ_1=0,32 is much lower compared to deep-drawing steel sheets which means that in ambient temperature it is possible to form only shallow and low complexity drawpieces.

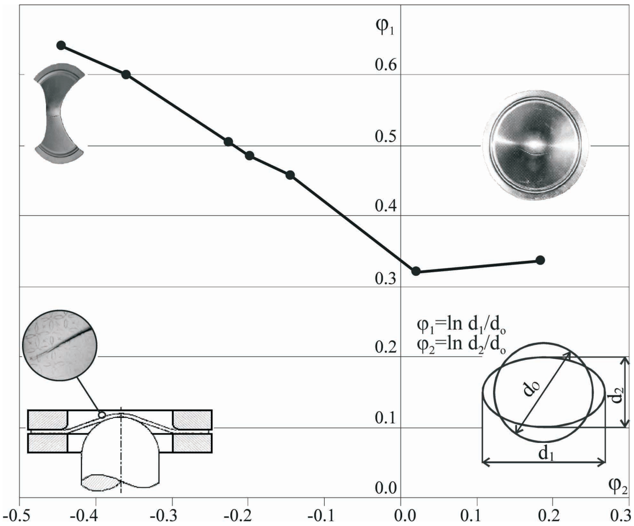

Fig. 1. Forming limit diagram FLD for CP2 titanium sheet

Figure 2 presents, for example, the test results of frictional coefficient obtained during the strip-drawing test in the presence of some technological lubricant and in dry conditions.

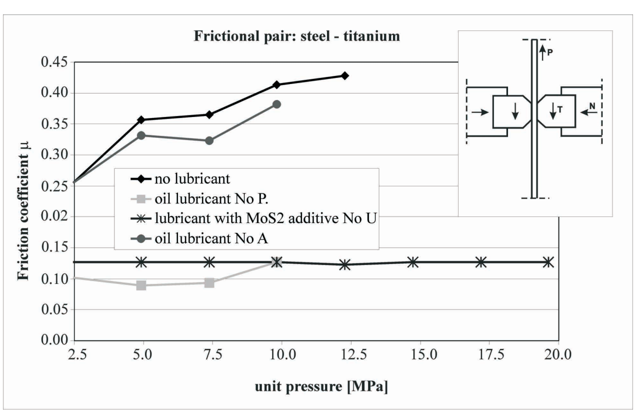

Fig. 2. Frictional coefficient for the frictional pair: "tool steel – titanium", and a scheme of the "strip-drawing" test; $P[N]$ – drawing force registered by a tensile machine, $T[N]$ – friction force, $N[N]$ – holding-down force

In case of sheet-titanium forming process the minimum frictional coefficient was obtained when oil lubricant with addition of molybdenum disulfide was applied. The frictional coefficient decreased from μ ≈0,3 for dry condition to μ ≈0,12. It is also necessary to emphasize that proper lubrication protects the tool from creation of titanium "build-ups", which makes production of the drawpieces with smooth surface impossible.

5. Numerical model

Analysis of the sheet-titanium forming process was carried out as a static process. The plastic-orthotropic model based on: the Hill yield condition, an associated flow rule and a proportional hardening rule was assumed in the numerical calculation of the sheet-titanium forming process. The Hill yield condition was given by equation (1), [12]:

$$F(\sigma_{bb}-\sigma_{cc})^2+G(\sigma_{cc}-\sigma_{aa})^2+H(\sigma_{aa}-\sigma_{bb})^2+ \\ +2L\sigma_{ab}^2+2M\sigma_{bc}^2+2N\sigma_{ac}^2-1=0, \tag{1}$$

where: a, b, c – the material principal axes, and F, G, H, L, M, N are material constants, which were calculated on the basis of Lankford coefficients: r_0 (for the rolling direction), r_{45} (for the direction 45° to the rolling direction), r_{90} (for the direction 90° to the rolling direction i.e. the transverse direction).
The plastic stress-strain curve was assumed to have the following analytical form:

$$\sigma_p = C(\varepsilon_o+\varepsilon)^n \tag{2}$$

in which ε_o is the initial yield strain, n is the strain hardening coefficient and C is a constant. Titanium sheet was modelled using 4-node shell elements, while the tools (die, punch and blank holder) were modelled using 4-node rigid elements, described in detail in [12].
Material data given in table 1 were used in the calculation. The other parameters have the following values: density ρ=4.5g/cm^3, Young's modulus E=110GPa, Poisson ratio ν=0.37, r values: r_0=2.30, r_{45}=6.16, r_{90}=4.72. The ADINA System assumes sliding friction between the tool and deformed material described with Coulomb law:

$$T = \mu N \tag{3}$$

in which frictional force T is proportional to the loading force N.
According to the test results the frictional coefficient μ=0.12 was assumed on the contact surface "die – deformed sheet – blank holder". Frictional coefficient μ=0.3 was assumed on the contact surface "punch – deformed sheet" although in the experiment both die and blank holder surfaces were lubricated. This means that, actually, the friction coefficient in the whole contact surface "punch - deformed sheet" is not as high as it was assumed in numerical model.

Figure 3 presents a numerical model of the stamping process. All degrees of freedom of the die nodes were fixed. The degrees of freedom of the punch nodes and blank holder nodes were fixed in X and Y directions.

The displacement of 40 mm in *Z* direction was applied to the punch. Holding-down force *F*=5kN was applied to the blank holder in – *Z* direction.

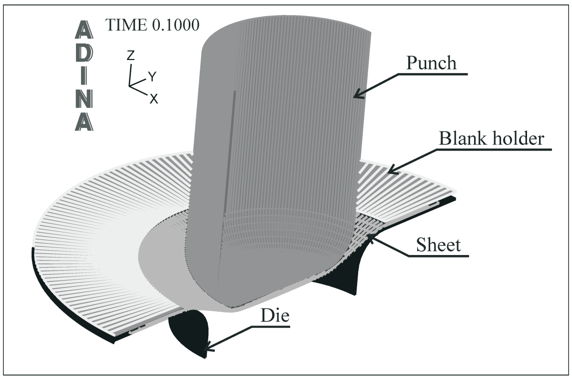

Fig. 3. Numerical model of the stamping process of cylindrical cup

6. The results of numerical simulation

Figure 4 illustrates the sample application of *FLD* during numerical simulation of the sheet-titanium forming process. As it can be seen in Figure 4 the comparison between strains in the cup and forming limit curve enables the assessment of the state of material effort possible and clears the way for producing good-quality cup at design stage. Excessive thinning of the deformed material increases the risk of cup cracking. In Figure 4a the fracture near the corner radius of the cup was marked with black colour. The strains in the cup significantly exceed the limit strains that can be transferred by the sheet. As a result fracture occurs. In this case it might be worth to consider the modification of technological process parameters such as: holding-down force, frictional conditions, shape and dimensions of the blank or replacing the current material with the one that has better drawability characteristics. In Figure 4b it can be seen that change of the process parameters (in the analysed case it was a decrease in holding-down force and frictional coefficient) and the choice of good input material shape and size improves material flow which results in more balanced distribution of strains. The strain values do not exceed the limit strain for the deformed sheet. This allows for avoiding fracture during stamping of the drawpiece. If the aforementioned measures do not result in more uniform strain distribution in the analyzed drawpiece the construction changes should be made, for instance, increase in the corner radius of the tool.

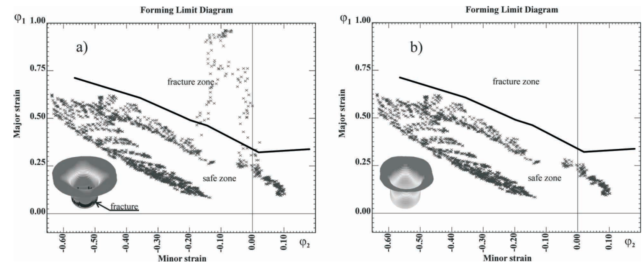

Fig. 4. Sample FLD application in numerical simulation of the sheet metal forming process: a) the cup with visible fracture resulting from the improper selection of forming parameters, b) the correctly formed cup obtained as a result of minimising the holding-down force, friction coefficient and blank diameter

In Figure 5 the influence of the tool geometry (corner radius for the die and punch) on the thinning of the cup wall is presented. As it can be seen in Figure 5 too small corner radius (in this case *r=3mm*) leads to the excessive thinning of the drawpiece wall near its bottom. As a result fracture occurs.

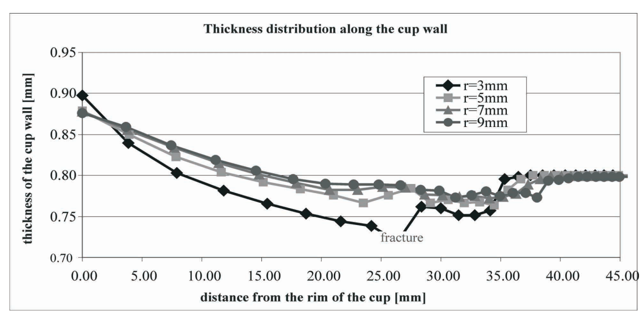

Fig. 5. Thinning distribution along the drawpiece wall – numerical calculation

During empirical validation the wall thickness of the real drawpiece was measured. Subsequently the numerical results were compared with actual ones. Sample comparison for the cup corner radius *r=6mm* is presented in Figure 6. It can be seen that both results are consistent. This indicates that numerical simulation can be applied during development of forming technologies for new titanium drawpieces and the corresponding stamping tools.

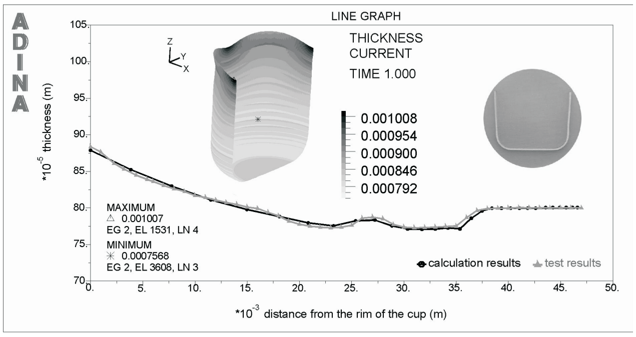

Fig. 6. Comparison between the test and calculation results – distribution of the wall thickness

7. Conclusions

The following conclusion can be drawn from this work:

– During classical sheet-titanium forming process with rigid tools, i.e. punch, die, blank holder, the non-uniform strain (thickness of the cup wall) distribution limits the depth of the drawpice. Thus the optimization of forming process should focus on minimizing the thinning of the drawpiece wall.
– Both tool geometry and friction, which can be reduced using proper lubrication, have impact on non-uniform strain distribution which leads to fracture of the drawpiece.
– The higher strain localisation and higher risk of fracture corresponds to the lower corner radius of the tool.
– During sheet-titanium forming processes the application of typical oil lubricants (e.g. lubricant No A – Fig.2), which are usually used in forming of the steel sheets, does not minimize frictional resistance in satisfying way. The lowest frictional coefficient was obtained for the lubricant with MoS_2 additive (lubricant No U)
– The results of numerical simulation depend largely on: accurate determination of material data of the deformed sheet and choice of appropriate mathematical model describing material (strain stress curve).

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