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Investigation of dependences of stress strain state properties on metal sheet holding force at its forming

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1. Introduction

The purpose of this investigation is to determine thinning variation (the 3rd marginal strain ε_3) at metal sheet forming and determination critical points on forming material. The main mechanical properties influencing forming condition is Young's modulus – E, density – ρ, yield stress – σ_y, ultimate tensile strength – σ_{UTS}, forming velocity – v, friction coefficient – μ (since we take friction coefficient as a dependence of relative velocity we do not account it as static and kinematic components but rather as single one). There were used a hypothesis which states that if thickness deformation from finite element analysis (FEA) coincides with experimental data, than stress strain relation from FEA can be treated as correct strength state of formed metal sheet part.

To complete this task we will vary blank holding force (BHF) to check its influence on material thinning or if it would have negative influence on the part's performance in formability we will see necking. Necking retardation [1-3] in metal sheet forming is one of the major defects. This paper will present the results from FEA – simulation of forming process of "Z" shape formed metal sheet part made from two different materials as well as thickness distribution in real experiment. Materials for testing were chosen by a reason: aluminium AW6802 (brittle and very non ductile), brass L63 (soft – very ductile). The output of simulation will be compared with physical tests.

The investigation was performed using 6 different load schemes of changing blank holding force. Since our investigation considers practical and finite element modeling (FEM) therefore firstly we consider carrying out an experiment and then we do modeling with LSDyna software. If holder uses relatively high value of suppressing force then metal sheet is forced not to slide over the punch/die surface, but if that relative force has value lower than tangential tension force that sheet starts to slide and therefore arises sliding frictional forces [4-6]. If the normal force *F* and tangential force *T* is applied onto a punch, then the system is in either equilibrium position or into movement with a constant velocity. The movement starts very slowly, that's why we do not consider dynamic effect in the stamping process. This is important because thickness distribution along stamped part varies and as more suppressing force we do use as we get more thinning in the particular regions we shall find those regions in our simulation model. Our model is constructed to simulate thickness distribution in the "Z" shape part. At the end of investigation one shall see how thickness distribution varies in accordance with metal sheet suppressing force. It needs to mention that we simulate constant blank holding force. Usually in metal production industries stamping is performed with not constant or not regulated BHF [7]. We ignore this error through fixing the holders movement towards blank. By doing that we assure that the gap between die and upper holder (the same is with punch and lower holder) is always not less than 2.9 mm and not bigger than 3.1 mm. So the gap is always within the range of $2.9 \le x \le 3.1$ mm, where x is characteristical gap value. We can fix the gap exactly to 3 mm because by doing this we will eliminate the use of BHF [7]. In other word there is use to regulate blank suppressing force.

2. Methods of investigation

Testing was conducting using two common models: experimental procedures (Fig. 1) and FEA (Fig. 5). Since the investigation concerns dynamic reaction in metal sheet forming – the FEA was conducted using program for nonlinear dynamic analysis of structures in three dimensions ls971 single R4.2. To simulate prestressed bolts in LSDyna we used new feature available only from current version firstly released in ls971s R3 beta. The keyword defining forces suppressing part is *INITIAL_AXIAL_FORCE_BEAM. This LSDyna card defines relative axial force to beam. Because in original stamping kinematical scheme the pressure objected to the material is defined by five M12 bolts which have torqued by 20 Nm force – moment in order to get 25200 N suppressed force (full suppressing force range defined in Table 2). According to initial set, 2 different types of materials have been examined. Main mechanical properties were gained from uniaxial tension test where true stress strain curves showed in Fig. 2 were determined. Initially, uniaxial test was carried out to evaluate the mechanical and ten-

Fig. 1 Experimental device

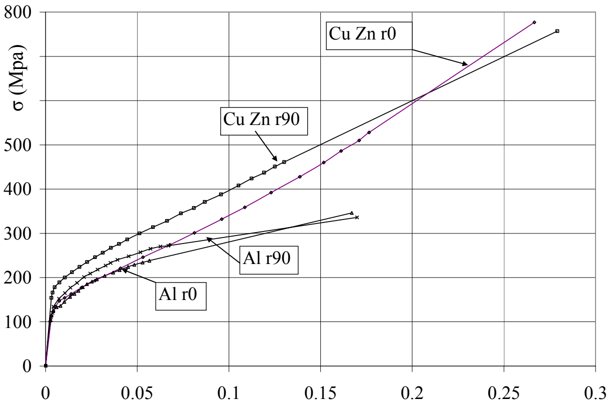

Fig. 2 True stress strain curves for tested materials

sile properties. Experimental procedure was carried out using different load schemes at the same punch traveling conditions. Load was applied on a lower holder. Force curve in LSDyna is defined with a card *LOAD_NODE_SET. For numerical calculation we used material model 24, defined keyword as *MAT_PIECEWISE_LINEAR_PLASTICITY. Literature [8] recommends not to use model 81 with damage effect since it gives unrealistic results in bending. The model was created with Belytschko-Tsay shell element with thickness stretch no 25 for part with 5 through thickness integration points and Belytschko-Tsay shell element no 2 for the rest of model with 3 through thickness integration points [6, 7]. To determine experimentally thickness distribution there computational model was introduced. This model is shown below in the Figs. 3 and 4. In Fig. 5 the same computational model but modeled with finite element method is shown. At the same Figure can be seen and mesh density On the FE model there are subscriptions of the main parts acting on metal sheet forming are set. As in real experiment we have: *1* – punch, *2* – metal sheet part before deformation, *3* – lower holder, *4* – stationary die, *5* – upper holder.

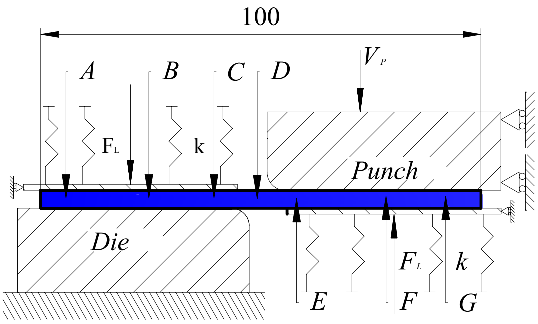

Fig. 3 Kinematics of model before forming

Measurements were taken from the cross-sections along the part. Basic position can be seen in Fig. 6. The part was divided into 2 equal zones. Calculations were made from the middle and from right hand side of the part cross-section. Since both outermost cross-sections are identical there is no use to measure the third cross-section at the same time. Boundary conditions applied to the model are described in the Table 1: it is set, that the formed part does not have any constrained degrees of freedom (DOF) since initially we do not know how it will perform in stamping. Punch and blank holding holders can move only in Z direction so we set only one DOF for unconstrained. The die has 6 DOF constrains and it can not move or rotate.

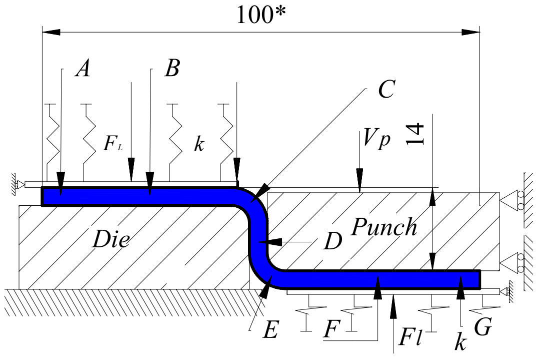

Fig. 4 Kinematics of model after forming and measuring points for characteristical stress points

Table 1

Boundary condition applied to model

Component	Displacement			Rotation		
	x	y	z	Θ_x	Θ_y	Θ_z
Punch	×	×	✓	×	×	×
Die	×	×	×	×	×	×
Upper holder	×	×	✓	×	×	×
Lower holder	×	×	✓	×	×	×
Blank	✓	✓	✓	✓	✓	✓

where ✓ - free, × - constrained

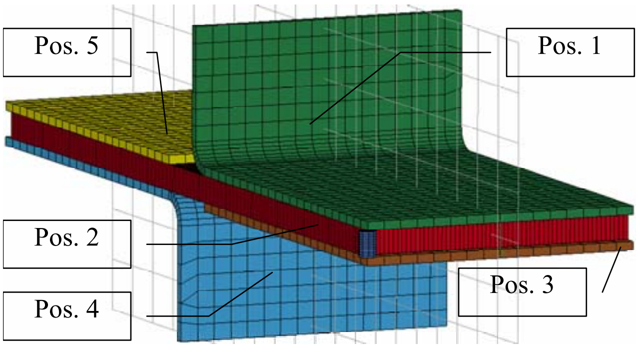

Fig. 5 General view of FE model with cross-section

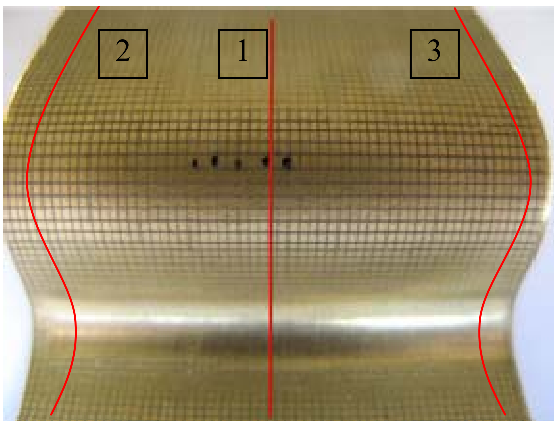

Fig. 6 Measurements were taken along the part

Experimentally formed part was made with 25 kN power press in KTU laboratory. In Table 2 also prescribed holders' suppressing force in relation to bolts torque is set. Deformation speed in all examined materials has the value of $\dot{\varepsilon}$ – 0.023s^{-1}. The described forming procedure modeled with FEA correlates exactly with experimental model.

Metal sheet suppressing force is regulated by wrenching up some bolts by adequate torque. Kinematics of stamping component can be seen in Fig. 3. Material models dimension are as following: 3×30×100 mm. This plate was initially precut from a bigger metal sheet in order to reduce residual stresses. Characteristical data needed to simulate stamping analysis is: stress strain curve, Poisson's ratio, and coefficients of friction. In the figure 2 can be seen mechanical properties for tested material L63 and AW6802. By designating R0 and R90 we mean, that material was tested along the rolling direction and reversely of rolling direction. Mechanical properties were used in FEA model. Analytical calculation of thickness is based on classical mechanics of metal sheet forming [7]. Since our investigation concerns only thickness or the 3rd marginal strain ε_3 we can calculate it as

$$\varepsilon_3 = ln\frac{t}{t_0} = -\frac{1}{2}\varepsilon_1 \qquad (1)$$

here ε_3 is 3rd marginal strain, t is thickness after deformation, t_0 is initial thickness, ε_1 is 1st marginal strain.

Table 2

Holders suppressing force sequences

Sequence	Torque, Nm	Axial force, N	Pressure, MPa
1	25	31500	22.37
2	20	25200	17.90
3	15	18800	13.35
4	10	12550	8.91
5	8	10100	7.17
6	7	8800	6.25

If the deformation runs on general plane stress sheet conditions are

$$\varepsilon_3 = -(1+\beta)\varepsilon_1 \qquad (2)$$

where β is defined as

$$\beta = \frac{\varepsilon_2}{\varepsilon_1} = \frac{ln(d_2/d_0)}{ln(d_1/d_0)} \qquad (3)$$

here d_0 is the undeformed state with circle and square grids marked on an element of the sheet, d_1 is the deformed state with the grid circles deformed to ellipses of major diameter d_1, d_2 is the deformed state with the grid circles deformed to ellipses of minor diameter d_2

$$\varepsilon_3 = -(1+\beta) ln\frac{d_1}{d_0} \qquad (4)$$

From Eq. 4 we have, that current thickness is

$$t = t_0 \, exp(\varepsilon_3) = t_0 \, exp\left[-(1+\beta)\varepsilon_1\right] \qquad (5)$$

If volume $td_1d_2 = t_0d_0^2$ is in constant, then final thickness is

$$t = t_0\frac{d_0^2}{d_1d_2} \qquad (6)$$

Before performing deformation of a sheet, we marked the investigated material with square grids [9] in order to investigate thinning effect. The dimensions of initial grid were 0.5 mm and 0.1 mm space between grids. In case of localized necking critical strain can be calculated [9]

$$\varepsilon_1 = \frac{n}{1+\beta} \qquad (7)$$

where n is strain hardening index [7].

In case of diffuse necking critical strain can be calculated from Swift equation [8, 9]

$$\varepsilon_1 = \frac{2n(1+\beta+\beta^2)}{(1+\beta)(2\beta^2-\beta+2)} \qquad (8)$$

Measurement points for analytical calculation were taken as shown in Figs. 3 and 4. Six different locations were measured. Point A and point B were taken in the horizontal position as well as points F and G. Only one point D was taken from vertical place of the part. And by single one at the position were bending deformation takes part (points C and E).

3. Investigation results

Experimental and finite element analysis revealed the following results depicted in figures below. Full development history of thinning in the part is shown in the Fig. 7. This is a view from material AW6082 R-90 formed with 31500 N holders suppressing force. The measurements were taken every second time steps to get nine thinning distributions along a part in accordance to punch travel distance. "0" point corresponds no punch movement; there is no deformation in the part. "16th" point corresponds the last step of punch on the traveling curve. The part should be deformed according to forming tools shape.

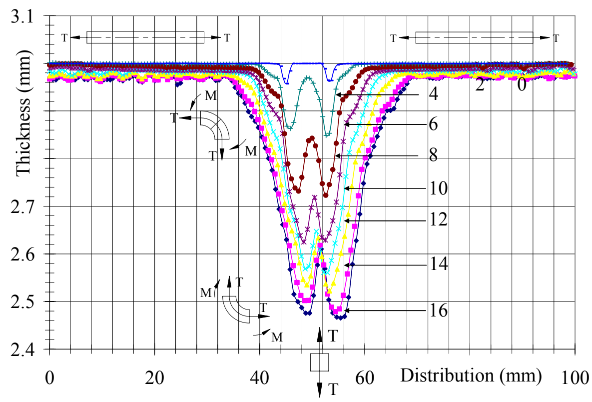

Fig. 7 Full development of thinning along a part

Table 3

Mechanical properties of tested materials

Material	Density ρ, kg/m^3	Yield stress σ_y, MPa	Ultimate tensile stress σ_{UTS}, MPa	Total elongation A_5, %	Young's modulus E, GPa	Deformation at fracture ε_{ut}	Poisson's ratio ν_0
AW6082 R-0	2700	130	225	16	75.7	0.17	0.33
AW6082 R-90	2700	136	230	19.8	87.6	0.169	0.33
L63 R-0	8440	165	313	38	106.4	0.279	0.36
L63 R-90	8440	132	293.7	50.13	105.1	0.262	0.36

In Fig. 7, results are taken from FEA, since we can not measure thinning in all steps. The experiment completed with the same blank holding force, formed part experienced a crack, so this figure is only used for theoretical examination. In the figure one can see upper and lower punch boundaries. When the punch is at the rest in upper position the part has it's thinning of 3 mm. When the punch starts to move slowly downwards, deformation begins and thinning takes a part. At holders suppressing force of 31500 N one shall see that the major thinning upstarts at the location of 40 and end up at the location of 60 mm along the part. In metal sheet forming it is vital to secure that thinning develops throughout the part and not only in the certain regions as we see in the Fig. 7 where one can find thinning only in the two regions. The highest values we found are around 2.5 mm. That is not acceptable. From literature [1] we know that it can be true, that the investigated sort of aluminium can not be deformed in a range of 31500 N of suppressing force because at the end of punch traveling in the material develops a crack. Another major concern one shall see in the same Fig. 7 is that thinning does not develop equally in vertical region of the part. We have part thickness value higher at the center of the part. Following part to the left or to the right from the center the thickness values develop lower values. Because of this phenomenon one can be explain why the crack develops not in the center of the part but rather a bit to the left or right from it. If left hand side differs from right hand side in the Fig. 7 and others we can explain it as the part initially is located on the die surface not exactly correct. The part shall be located exactly in the center of the forming tools in order to receive adequate results on both hand sides.

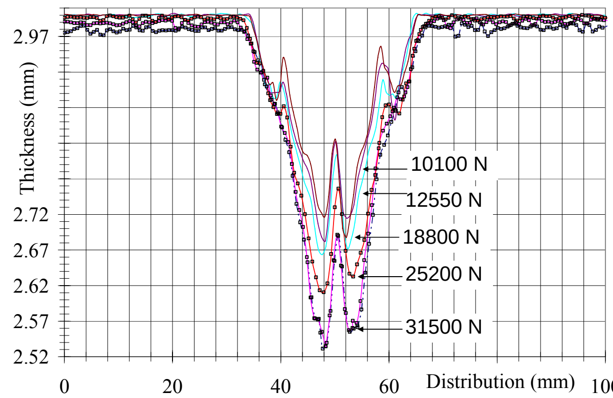

Fig. 8 Thickness distribution depending on blank holding forces for material CuZn R0 along a part sides

During deformation of sequence from 1 to 6 (Table 2) with adequate holders suppressing force one can see in the Fig. 8. The following figure is created for CuZn.

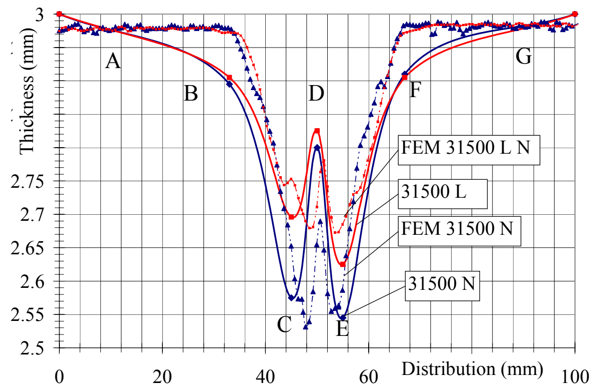

Fig. 9 Part thickness. Experimental data versus FEA data. Material CuZn 31500 N along a part

Mechanical properties of the investigated materials one shall see in the Table 3.The most material thins out when holders suppressing force is hypothetical – 31500 N. Material changes its thickness by the same manner throughout all suppressing force sequence – it has two peaks at some distance from the center. Fig. 9 represents material thinning for CuZn R0 versus Finite element data. The given data nicely fits experimental and FEA data. From this figure we make an assumption that the data from FEA is correct since it perfectly matches the data from experiment observation. On the thinning curves there also is set a characteristic points which are taken from some particular places on deformed part. Points A, B,…,G correspond points on undeformed part at the Figure 3 as well as on the deformed part at the Fig. 4. As experimental data revealed the major concern we need to account is points C and E, because at these positions (or points) are the most relevant to develop a crack. No cracks will occur at the location with point D (Fig. 9). Fig. 10 corresponds adequately thinning variations for materials Aluminium AW6082. Since we made an assumption that the 3rd deformation from FEA perfectly matches experimental date we believe that stress strain at the important point is also correct. Comparison of major thickness distribution in investigated materials can be seen in the Fig. 11. Fig. 12 is stress strain curves for materials aluminium and brass at specific points. Needless to say that material brass has steeper stress strain curve (Fig. 2), Fig. 12 justifies this tendency. The more steeper the curve in monoaxial stress strain the more steeper is stress strain at specific points at deformable part. Fig. 13 is final results from experiment where shall be found a thickness in metal sheet forming, when controlling blank displacement. There clearly can be seen a tendency, that both investigated materials have linear dependency on *BHF*. Since thinning distribution on left hand side and right hand side is the same we marked this with P2 and P3 in Fig. 13 above. In the middle of the part thinning distribution is marked with P1. Optimum *BHF* is within a range of $18800 \le BHF \le 25200$ if thinning is within the range $2.6 \le x \le 2.8$.

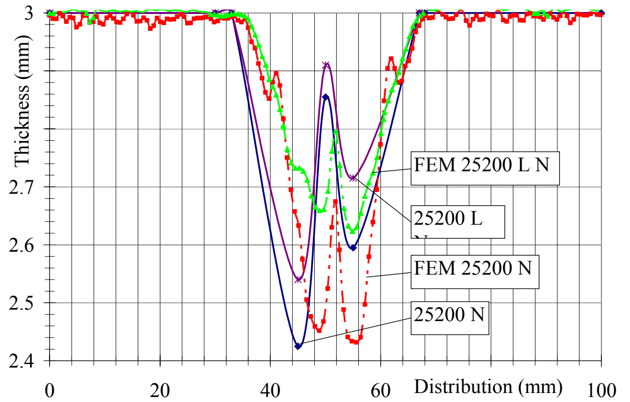

Fig. 10 Part thickness. Experimental data versus FEA data. Material Aluminium 25200 N along a part

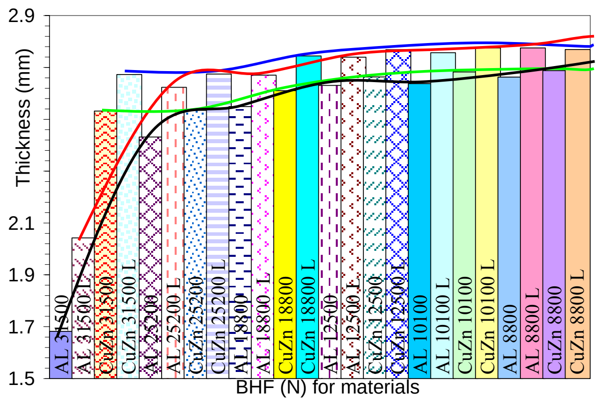

Fig. 11 Comparison of major thickness distribution in investigated materials

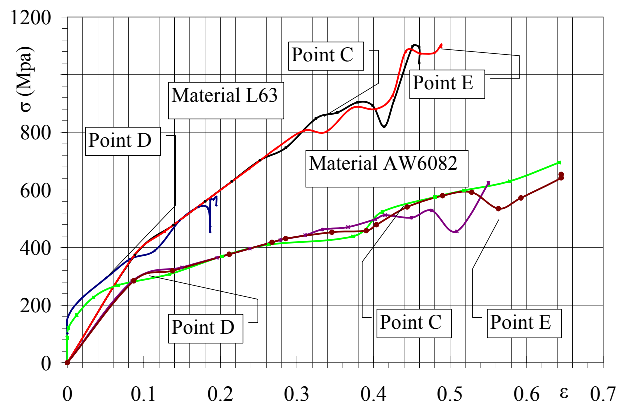

Fig. 12 Stress – strain curve at specific points for investigated materials

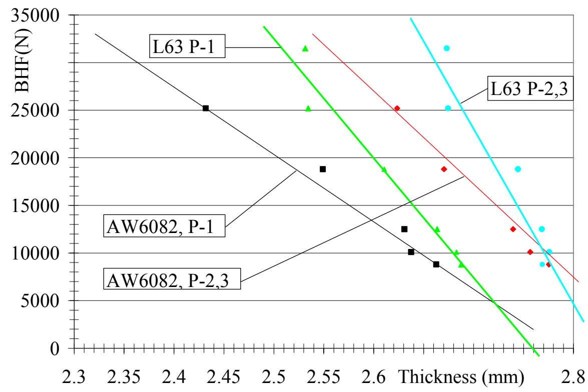

Fig. 13 Blank holding force versus thickness

4. Conclusions

In the paper we discovered how thinning takes part in metal sheet, while deforming "Z" shape element. Seven main locations were measured along the part. The optimal holder holding force was proposed by which metal sheet least thins out. The investigations were carried out using two common methodologies - experimental methodology and finite element methodology. In FEA measurements were taken after spring back calculation. Two material models were tested under the various load ranged from 31500 N to 8800 N. The analysis was made at ambient temperature.

The obtained thinning properties for tested materials at room temperature showed that increasing of blank holder suppressing force causes increasing material thinning. Experimental data revealed that thinning is not monotonous and increases at the corners of forming tools. The vertical part of deformed part also thinned out but not so as at the corners. No thinning took part at the place where blank holders touches forming material. After comparison of experimental data and the data from finite element analysis conclusion was set, that the 3rd strain fully coincides between methodologies. If this is true then fraction strain calculated from FEA is suppose to be correct. In final remark we sum up experiment data and concluded as 2 major outcomes:

1. In general, investigated materials aluminium AW6082 and brass L63 thinning effect as function of blank holding force thins out accordingly to linear relationship not depending of the place where measurements were taken.

2. The highest stress points were determined and critical points on deformed part were set where possibly a crack can be initialized.

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ĮTEMPIŲ IR DEFORMACIJŲ BŪVIO PRIKLAUSOMYBĖS NUO FORMUOJAMO METALO LAKŠTO PRISPAUDIMO JĖGOS TYRIMAS

R e z i u m ė

Šis darbas yra ankstesnių darbų tęsinys. Darbe nagrinėjama aliuminio AW6802 ir žalvario L63 lakštų įtempių ir deformacijų būvio priklausomybė nuo formuojamo lakšto prispaudimo jėgos. Atliktas eksperimentinis tyrimas bei skaičiavimai baigtinių elementų metodu ir gautas geras rezultatų atitikimas. Ištyrus lakštų suplonėjimą, buvo nustatyti kritiniai taškai, kuriuose galimai įvyksta medžiagos suirimas. Nustatyta lakšto prispaudimo jėgos įtaka lakšto storio deformacijai ir reikiama prispaudimo jėga, kuriai esant lakšto deformacija mažiausia.

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INVESTIGATION OF DEPENDENCES OF STRESS STRAIN PROPERTIES ON METAL SHEET HOLDING FORCE AT ITS FORMING

S u m m a r y

The present paper is a continuation of other papers of the author. In this paper author examine aluminium AW6802 and brass L63 metal sheets stress strain state condition dependencies form forming material blank holding forces. There were conducted an investigation using two common methodologies: experimental and finite element method. There were gained a good correlation of investigation results between two common methods. After examinations of thinning of metal sheet forming there were gained critical points, where exists the highest possibility for initialization of the crack. There were determined metal sheet holding force and it's influence to investigated metal sheet thickness strain. Also there were determined needed blank holding suppressing force under which metal sheet thins out the least.

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ИССЛЕДОВАНИЕ СИЛЫ СЖАТИЯ ЛИСТОВОГО МЕТАЛЛА В ЗАВИСИМОСТИ ОТ НАПРЯЖЕНИЯ И СОСТОЯНИЯ ДЕФОРМАЦИЙ

Р е з ю м е

Настоящая работа является продолжением предидущих работ.

В статье рассматривается зависимость напряженно деформированного состояния алюминиевых AW6802 и латунных Л63 листов от силы прижатия формируемого листа. Проведены экспериментальные исследования и расчет методом конечных элементов, получена хорошая совпадение результатов. Изучив утончение листового металла, были получены критические точки, в которых возможна начало разрушения. Установлена сила прижатия листа и ее влияние на деформацию толщины исследуемых листов металла. Также была определена необходимая сила прижатия, при которой деформация листа будет наименьшая.

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