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THE EFFECTS OF FRICTION ON STAMPING PROCESS OF SHEET METALS USED IN AVIATION

WPŁYW TARCIA NA PROCES TŁOCZENIA BLACH STOSOWANYCH W LOTNICTWIE

An important factor in the possibility of obtaining correct drawn parts with the desired functional properties is the friction between the stamped sheet and the tool.

The article discusses the impact of technological lubricants developed according to our own formulas, based on vegetable oils, on the stamping process taking into account the strain distributions in the drawn parts. Biodegradable lubricants based on rapeseed oil with an addition of stearic acid or boric acid were used. The results of the friction coefficient in a strip drawing test and the numerical analysis results of the stamping process of a spherical cap from sheet metal: aluminium 2024, commercially pure titanium Grade 2, steel 5604 in dry friction and lubrication conditions, are presented. Strain distributions and changes in the drawn part wall thickness were analysed.

Keywords: sheet, sheet-metal forming, friction, technological lubricant

Istotnym czynnikiem decydującym o możliwości uzyskania poprawnych wytłoczek o żądanych właściwościach użytkowych jest tarcie występujące pomiędzy tłoczoną blachą a narzędziem. Tarcie występujące w procesach obróbki plastycznej ma bezpośredni wpływ na: rozkład naprężeń i odkształceń w objętości kształtowanego materiału, graniczną - możliwą do uzyskania wysokość wytłoczki oraz wielkość siły tłoczenia. Podstawowym sposobem ograniczania wielkości oporów tarcia w obróbce plastycznej jest odpowiednie smarowanie. Dodatkowo smary technologiczne zapobiegają bezpośredniemu kontaktowi obrabianego materiału z narzędziem, a tym samym zacieraniu i nalepianiu kształtowanego materiału na powierzchniach roboczych narzędzia, przez co znacząco wpływają na jakość otrzymywanych elementów oraz trwałość narzędzi. Smary dobiera się do konkretnych procesów oraz rodzaju kształtowanych materiałów, wielkości nacisków, stanu współpracujących powierzchni oraz prędkości poślizgu i temperatury pracy. Wpływ poszczególnych czynników na opory tarcia jest złożony i wymaga prowadzenia szeregu badań doświadczalnych z zakresu przydatności smaru technologicznego do poszczególnych procesów formowania.

W artykule omówiono wpływ smarów technologicznych opracowanych według własnych receptur na przebieg procesów tłoczenia z uwzględnieniem rozkładów odkształceń w wytłoczkach. Zastosowano biodegradowalne smary oparte na olejach roślinnych tj. oleju rzepakowym z dodatkiem kwasu stearynowego lub kwasu borowego. Przedstawiono wyniki badań współczynnika tarcia w próbie przeciągania pasa blachy oraz wyniki analiz numerycznych procesu tłoczenia czaszy kulistej z blach: aluminiowej 2024, tytanowej Grade2 i stalowej 5604 w warunkach tarcia technicznie suchego oraz w warunkach smarowania. Analizowano rozkłady odkształceń oraz zmiany grubości ścianek wytłoczek.

1. Introduction

In addition to the existing trend towards the development of lightweight and durable materials used in aviation, there is the desire to design and manufacture aircraft structures of sheet metal. Among the various production techniques, only sheet-metal forming enable the production of thin-walled components with high strength [1-4]. According to [5,6], the tribological properties of the deformed materials and the friction conditions are important factors determining the results of sheet metal forming, particularly in the deep drawing process. Friction increases the drawing force, and as a result deteriorating energy efficiency of the process. High friction resistance at the blank holder – blank – die interface causes a rise in the drawing force and increases the risk of cracking of the drawn part, which has particular significance in forming sheets of small thickness [7]. Additionally, friction has an impact on the strains distribution in the drawn part as well as on the changes in the thickness of its walls [8].

The negative effects of frictional forces are uneven strain, temperature rise in the workpiece - tool interface and lubrication deterioration, which in turn affects the quality of the drawn parts and tool life. The set of tribological processes occurring during formation in the tool contact zone, including mechanical and adhesional friction surface interaction as

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well as the impact of the lubricant, significantly affect the state of the surface layer of the product and the tools [9].

The friction forces in the process of sheet metal stamping can also have a positive effect on its course. A high friction coefficient between the deformed sheet and the punch surface exerts an increase in the force required to break drawn part, which is a factor facilitating sheet-metal forming. Therefore the aim should be to reduce the frictional resistance at the blank holder - deformed metal – die interfaces, not eliminating friction between the punch and the deformed sheet.

Reducing frictional resistance in the forming process, thus improving product quality, can be achieved by appropriate selection of the tool surface layer properties, or by the use of process lubricants. In many cases, a mere application of coatings on the tools protects against wear, but it is not sufficient to effectively reduce the friction and hence total elimination of process lubricants, despite their many shortcomings, is often impossible. Research in this direction is focused on the development of hard coatings with improved tribological properties, which enable the elimination of lubricants [6,10-13]. In [14] the friction coefficient values when stamping an aluminium coated steel sheet in dry friction conditions and in the presence of a lubricant as well as with a variable die surface roughness were evaluated. As emphasized by the authors of [15], determining the friction coefficient in the sheet forming process is difficult, labour intensive and very costly, because many factors affect friction mechanisms, and thus the obtained results. The experimental studies presented in the literature [16-18], using methods that reflect the process conditions, are aimed at searching for new lubricants with improved tribological properties, and also safe for the environment. Most of the applied lubricants are not only harmful to the environment but are also difficult or even impossible to completely remove from the product [11, 19]. High demands are set for process lubricants such as ease of application onto the tool or sheet, ease of removal from the product and environmentally safe waste disposal as well as lack of negative impact on living organisms and the surrounding environment [20, 21]. In the scope of tribology, reducing the amount of waste and limiting the use of volatile organic solvents used to remove lubricants from the drawn parts are expected [22-26]. In analysing the tribological aspects of lubrication in sheet metal stamping processes, research should focus on the possibility of using environmentally friendly lubricants. Although most process lubricants used for sheet-metal forming operations belong to the group of lubricants based on mineral and synthetic oils, the authors of [20, 26-28] believe that the alternative may be a vegetable oil. These oils due to the presence of long-chain fatty acids provide good lubrication under boundary friction [29]. In [20, 26, 28, 30, 31], the possibility of improving the friction conditions by introducing an additive in the form of boric acid to vegetable oil was analysed.

Numerical simulations play a significant role in the optimization of forming processes as they shorten the design process and reduce costs [8, 32]. Unfortunately, in most applications the phenomenon of friction cannot be accurately described, and therefore it should be kept in mind that friction and contact conditions accordingly adopted in the numerical model of the sheet metal forming process significantly influence the obtained calculation results.

The paper presents the results of friction coefficient tests for selected sheets of aluminium, steel and titanium, in the presence of ecological lubricants of our own formula, as well as the results of experimental testing and numerical simulations of the spherical cap forming process using the analysed metals, taking into account different forming process conditions.

2. Aim and scope of research

The main aim of the study was to determine the friction coefficient in the so-called strip drawing test performed in dry friction and in the presence of ecological lubricants formulated based on rapeseed oil and additives in the form of boric acid (H_3BO_3) and stearic acid ($C_{18}H_{36}O_2$). The study was conducted on sheet metal used in aviation: aluminium 2024, commercially pure titanium Gr 2 and steel AMS 5604, cooperating with a tool made of tool steel NC10. The view of the device enabling friction force and the clamping force measurements of the tool working parts on the sheet surface is shown in Figure 1.

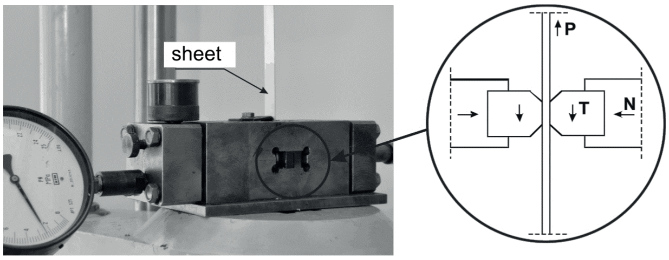

Fig. 1 Measurement of friction coefficient: a) view of device, b) strip drawing test schema: P - pull force, N – clamping force, T - friction force

Assessments of the impact of the prevailing friction conditions, corresponding to conditions of dry friction and lubrication conditions on the drawability of the examined sheets are based on the results of experimental and numerical simulations of the stamping process. Experimentally, in the stamping process of a spherical cap using a rigid tool, the influence of lubrication on the maximum realizable value of the drawn part depth and drawing force was set.

The analysis of the effect of technological lubricant on the plastic strain distribution in the deformed material and changes in drawn part wall thickness during drawing the tested sheets was based on a numerical simulation of the sheet-metal forming process. Numerical calculations were performed using the PAMStamp 2G program, dedicated to sheet metal forming processes.

3. Results of experimental studies

The results of friction coefficient tests as a function of unit pressure for the analysed friction pairs: ‘steel - aluminium’, ‘steel - titanium’ and ‘steel - steel’ determined in dry friction and using lubricants based on rapeseed oil with an addition of boric (1 .11B) and stearic (l.11S) acids are shown in Figure 2.

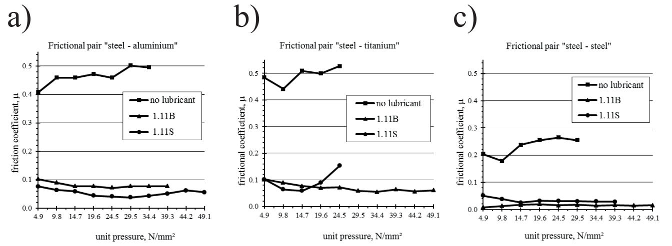

Fig. 2. Friction coefficients in presence of lubricants l.11B with addition of boric acid and l.11S with addition of stearic acid as well as in dry condition for friction pairs: a) ‘steel - aluminium’, b) ‘steel - titanium’, c) ‘steel - steel’

As seen in the presented results, in the case of the friction pair ‘steel - aluminium’, lubricants based on vegetable oils with additives cause a significant reduction in the friction coefficient of μ=0.4-0.5 for the conditions of dry friction to μ=0.05-0.08 in the case of rapeseed oil lubricant with the addition of stearic acid (l.11S). In the entire load range, the presence of lubricants prevented galling and sheet material adhesion to the working surface of the tool. In the case of the friction pair ‘steel – titanium’, only the addition of boric acid gave a reduction in the friction coefficient from μ=0.5 to μ=0.05 over the range of applied loads. The lubricant with the stearic acid addition provided a friction coefficient reduction only in the range of unit pressure to 25 N/mm^2, above which, like in the case of no lubrication, the material seized in the tool. The largest decrease in friction coefficient for the friction pair ‘steel - steel’ was observed when using rapeseed oil with the addition of boric acid (l.11B). The friction coefficient value decreased from μ=0.2-0.3 to μ=0.05. Analysing Fig. 2, greater effectiveness of the addition of boric acid can be seen in the case of lubricating the friction pairs ‘steel - titanium’ and ‘steel - steel’ compared to the friction pair ‘steel - aluminium’, for which favourable lubrication conditions occurred when applying oil lubrication with the addition of stearic acid.

The effect of the tested lubricants on the drawn part depth of a sample obtained using Erichsen cupping test is shown in Figure 3. The tests were conducted on metal discs with a diameter of 60 mm and a thickness of 0.8 mm, in which a spherical punch with a diameter of 28 mm was stamped. The discs were attached between the blank holder and the die with a fillet radius equal to 5 mm.

Both in the case of the aluminium sheet as well as the steel sheet, a properly shaped drawn parts could not be obtained, irrespective of the friction conditions. In the conditions of technically dry friction, material fracture of the drawn part occurred at a depth equal to respectively 9.0 and 9.2 mm.

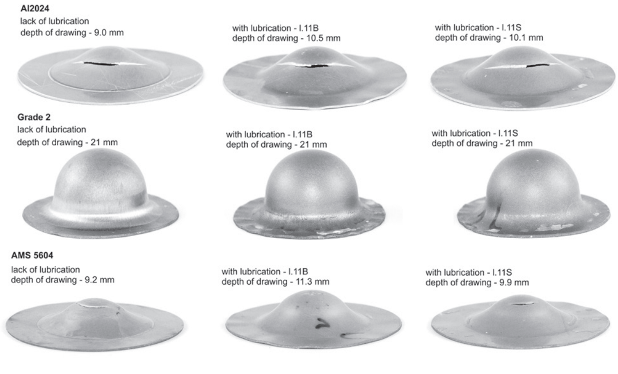

Fig. 3. Effect of lubrication on spherical cap drawing process

However, use of the examined organic lubricants yielded a higher drawn part, wherein the preferred lubricant was found to be with the boric acid addition. Using this lubricant, aluminium stamping fracture occurred at a stamping depth of 10.5 mm and at the stamping depth equal to 11.3 mm in the steel drawn part. In the case of the titanium sheet, we were able to obtain a proper drawn part regardless of the prevailing friction conditions. Lubrication allowed in this case a reduction in the punch force of 41000 N with no lubrication to 28000 N utilizing the lubrication oil with the addition of boric acid and 30000 N employing the lubrication oil with the addition of stearic acid.

4. Numerical analysis results

Within the numerical analyses, simulations of the spherical cup stamping process were carried out with the analysed sheet metal. The three-dimensional geometric model of the tool was developed based on the dimensions of the actual tools used in the experimental studies. The influence of the friction conditions on the plastic strain distribution and thinning of the drawn part material, especially at the moment of fracture was analysed. The calculations assumed isotropic sheet strength properties. The material data necessary to carry out numerical simulations such as yield strength *YS* (or 0.2% proof strength $R_{p0.2}$), ultimate tensile strength *UTS* and the material constant *K* as well as strain-hardening exponent *n* determined experimentally in the static tensile test are presented in Table 1. The friction coefficient values, taking account of the stamped material, corresponding to the conditions of dry friction on the contact surface with the punch and lubrication conditions on the contact surfaces of sheet – blank holder and sheet – die were adopted on the basis of the average of friction coefficient values obtained in the strip drawing tests. Preliminary experimental studies and numerical simulations of the sheet metal forming process allowed for optimal adjustment of the pressure in terms of reducing the phenomenon of sheet wrinkling.

TABLE 1.

Mechanical properties of materials used in numerical calculations

Parameter	Young's modulus E, GPa	Offset yield point $R_{p0.2}$, GPa	Ultimate tensile strength UTS, GPa	Poisson's ratio ν, -	Density ρ, kg/m^3	strength coefficient K, GPa	Strain hardening exponent n, -
Grade 2	105	0.236	0.316	0.37	4500	0.465	0.125
Al2024	73	0.313	0.457	0.33	2800	0.593	0.151
AMS 5604	196	1.040	1.160	0.27	7800	1.288	0.039

The results of the numerical calculations for the spherical cup stamping process using the tested sheets taking into account the different friction conditions are shown in Figures 4-12. The plastic strain distributions in the aluminium drawn part, obtained during stamping in dry friction conditions, at the moment of fracture as compared to the strains which take place during stamping with lubrication are shown in Figure 4. In the absence of lubrication, material fracture occurred in the drawn part at a punch depth equal to 9.1 mm, while in the conditions of lubricated die and blank holder at such a punch depth, there were no hazardous areas due to the loss of cohesion of the drawn part material.

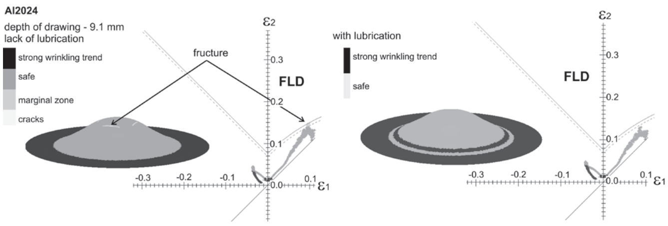

Fig. 4. Comparison of strains in stamped aluminium sheet obtained in dry friction and lubrication conditions, stamping depth - 9.1 mm

The numerical calculation results of plastic strain e and the thinning of the aluminium drawn part wall as a result of the forming process are shown in Figures 5 and 6. Peripheral plastic strain distribution of the sheet material and the accompanying thinning of the drawn part wall, typical of axisymmetric drawn parts, can be observed. The highest values of plastic strains occur in the area of the apex of the drawn cup, this place also shows significant thinning of the deformable material, which can be reduced by proper lubrication.

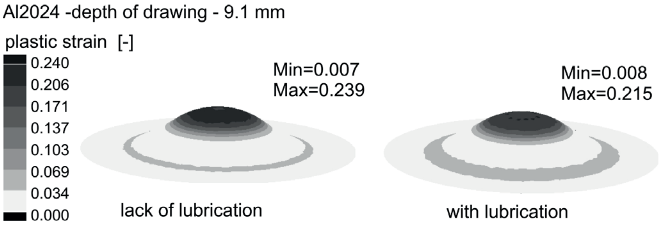

Fig. 5. Strain distribution on aluminium drawn part surface in dry friction and lubrication conditions

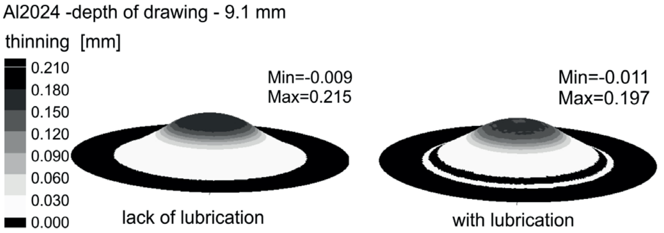

Fig. 6. Thickness distribution of aluminium drawn parts in dry friction and lubrication conditions

The numerical simulations results of the spherical cap stamping process of drawn parts from titanium Grade 2 sheets are shown in Figures 7 - 9. The applied lubrication allowed in this case for a more even plastic strain distribution in the drawn part material and significantly reduced thinning of the drawn part walls. The increase in thickness of the sheet of the stamping flange is caused by the presence of compressive stress in the peripheral area.

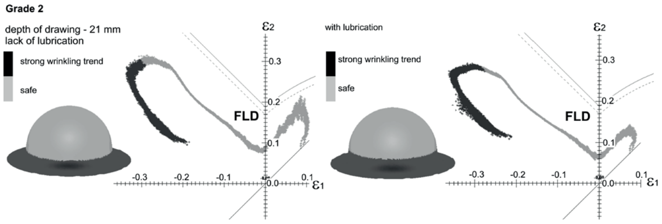

Fig. 7. Comparison of strains in titanium sheet drawn parts obtained in dry friction and lubrication conditions at depth - 21 mm

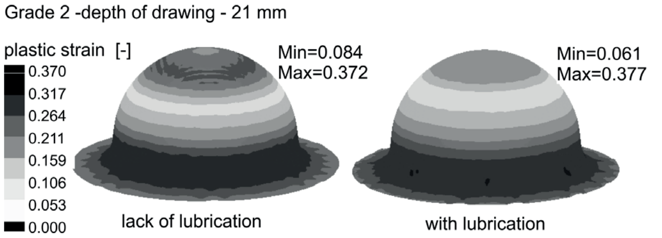

Fig. 8. Strain distribution on titanium drawn part surface obtained in dry friction and lubrication conditions

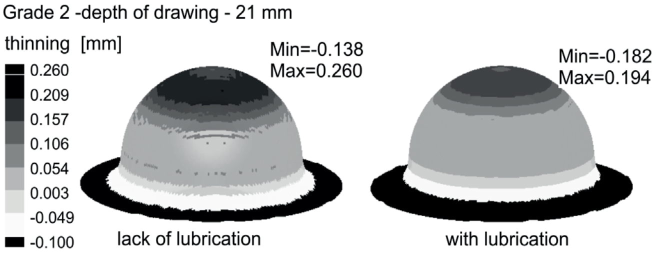

Fig. 9. Thinning of titanium drawn part walls received in dry friction and lubrication conditions

The comparison of strains present in the steel drawn parts obtained in different friction conditions are shown in Figure 10. In the conditions of dry friction, with a depth equal to 9.4 mm, in the drawn part material area, a fracture zone occurs, corresponding to points located above the forming limit curve. At the same depth, and using lubrication, there was no fracture of the material, however, the strains are located near the danger zone, threatening the loss of material cohesion.

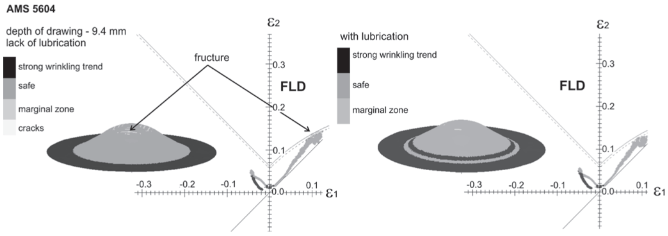

Figure 10. Comparison of strains in stamped steel sheet obtained in dry friction and lubrication conditions at depth - 9.4 mm

As in the case of aluminium drawn parts, lubrication provides a more uniform strain distribution, less thinning of the drawn part walls, and allows for a slightly larger stamping depth (Figs. 11 and 12).

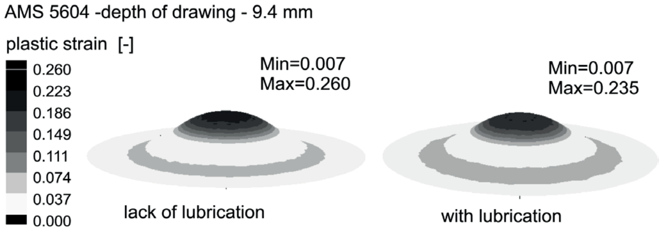

Fig. 11. Strain distribution on steel drawn part surface obtained in dry friction and lubrication conditions

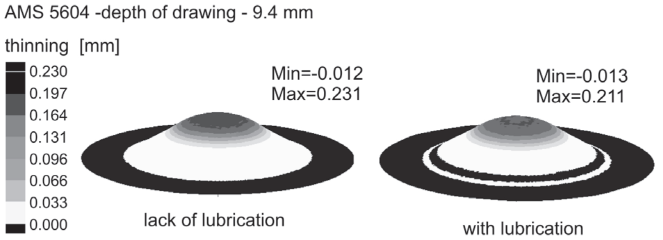

Fig. 12. Thinning walls of steel drawn parts received in dry friction and lubrication conditions

5. Summary

The presented results of the study showed that organic lubricants based on vegetable oil developed from our own formulas can be used to improve the sheet metal forming processes of difficult-to-form sheet metal used in aviation. Boric acid, and stearic acid were used as the additives used for the lubricants production. The use of boric acid as the boundary friction factor was based on the similarity of its structure to that of graphite crystalline particles, which is commonly used as an additive for reducing friction. Layered crystal compounds such as graphite and boric acid have well-defined slip planes to determine their lubricating properties. The friction coefficient tests confirm the effectiveness of applying lubricants based on rapeseed oil with the addition of boric acid as a lubricant in the stamping process of titanium and steel sheets. The presence of boric acid resulted in a marked reduction in the friction coefficient and prevented galling in the pair of friction elements 'steel-titanium' and 'stainless-steel'. Through the use of lubrication, the steel sheets attained a stamping depth of 23% relative to unlubricated sheets. However, in the case of the titanium sheet, the applied lubrication reduced the stamping force by 32% relative to the sheet not covered with lubricant.

In the case of the friction pair 'steel-aluminium', effective separation of its components within the whole load range and improvement of the tribological conditions to the greatest extent was assured by a rapeseed oil based lubricant with a refining addition in the form of stearic acid. Stearic acid is a fatty acid with a long carbon chain, which is often added to lubricants due to the fact that it effectively separates the friction surfaces. Owing to lubrication in the case of aluminium sheet stampings, a greater depth of 14.5% was obtained relative to unlubricated sheets.

Numerical simulations (FEM) of the stamping process, conducted simultaneously with the experimental research, enable one to assess the formability of a given type of sheet metal and to analyse the plastic strain of the drawn part material during the stamping process for different friction conditions. The obtained experimental results showed that the stamping depth depends significantly on the friction between the deformed material and the tool. Analysis of the numerical calculation results of the forming process reveals a pronounced effect on the lubrication distribution and plastic strain of the material, thickness changes in the drawn part, and thus the depth of drawn part without defects.

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