Frictional Resistances of AMS5599 Nickel-based Alloy at High Pressure Conditions

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Abstract. The frictional resistance plays a key role in sheet metal forming processes, especially in automotive and aerospace industry. The AMS5599 nickel-based alloy is hard to form heat and corrosion resistance material, and requires special forming conditions. In this paper, frictional resistances of 1-mm-thick AMS5599 alloy sheets were evaluated using a simulator of strip drawing test. The tests were conducted at dry friction conditions and under lubrication of machine oil and chlorinated honey-type stamping oil. The nominal contact area of the specimens with countersamples has been determined numerically using the finite element-based MSC.Marc program. The results of experiments show that the friction coefficient decreases with an increase of nominal pressure. The sheets tested exhibit high strengthening phenomenon that limits an increase of contact area under normal load.

1. Introduction

Due to the increasing quality requirements of components used in the construction of modern mechanical systems such as aircrafts, it is necessary to use materials with increased thermal and mechanical resistance. The basic building material of fan engines, for instance, are corrosion-resistant steels, and nickel-based alloys characterized by a favorable combination of high strength, high hardness and high corrosion resistance at operating temperatures above 300ºC. The use of corrosion resistant high-strength materials characterized by low plasticity (i.e. the ratio of the yield stress to tensile strength) for the production of aircraft engine parts cause problems related to the correct selection of forming operations [1]. Though high-strength alloys are mostly formed at elevated temperature, cold forming conditions are also used for non-complicated parts fabricated by, for example bending. The geometrical complexity of the drawpieces requires knowledge of the values of the elastic springback of the material which, when forming high-strength sheets, reach significant values. One of the main factors determining the high quality of the drawpieces is also the value of sheet metal thinning [2]. The heterogeneity of the deformation of the drawpiece depends primarily on the occurrence of friction forces at the interface of the deformed material and tool. The processes occurring in the contact zone are also influenced by the value of normal pressure, the type of material and the topography of both the sheet surface and the tool, and the type of lubricant [1, 3].

During the sheet metal forming, the value of forming force, slip velocities occurring in different areas of the part formed and temperature are changed. The non-uniformity of the deformation of the drawpiece is mainly determined by the occurrence of friction forces at the interface of the deformed material and tool. The processes in this interface are influenced by many factors including: the amount of normal pressure, material types of contact pair, the rate of deformation, the surface topography of
the sheet and tools, lubricant and temperature of the forming process [4, 5]. The factors dependent on the process include the amount of normal pressure, and the rate of deformation. The amount of normal pressure affects the real contact area that is smaller than the nominal area of contact. The evaluation of the contact area is very difficult and requires the knowledge of real surface topography. In order to find the real area of contact, some numerical approaches are reported [6, 7].

The unfavorable effects of frictional resistance include [5, 8]: non-uniform deformation of the sheet material, an increase in the pressure forced by the punch causing the risk of crack formation in the drawpiece wall, and worsening the surface quality of the element formed. The value of the resulting frictional resistances is mainly determined by the shear strength of the friction joints between surface asperities [9]. Large deformation values in the micro-areas of the contact favor the formation of non-diffusion adhesive joints (so-called adhesion). The tendency to ploughing is mainly observed in the case of contact of sheet and tool surface characterized by high surface roughness. Many experimental tests were developed to study the friction conditions in metal forming. For instance, an extensive review and discussion of tribological tests used in sheet metal forming processes were presented by Dohda et al. [10] and Wang et al. [11]. The strip drawing test can be considered as a universal test to describe the contact phenomena at flat surfaces of the sheet in sheet metal forming.

The knowledge of contact conditions is a key factor influencing the design of sheet metal forming technology. In this paper, the strip drawing test has been used to investigate the frictional resistances of AMS5599 nickel-based alloy. The experiments were carried out at three lubrication conditions, and different normal pressures. To find the nominal area at elastic-plastic contact, the numerical simulations in ABAQUS program were carried out.

2. Material and method
The mechanical parameters of 1-mm-thick AMS5599 alloy sheet were determined through the uniaxial tensile test in the universal testing machine. The chemical composition of the tested material is listed in Table 1. The mechanical properties determined in this test (Table 2) are yield stress \( R_{p0.2} \) anisotropy coefficient \( r \), strain hardening coefficient \( K \) and strain hardening exponent \( n \). The roughness parameters, i.e. the roughness average \( Ra \) and the 10-point peak valley surface roughness \( R_z \) were measured using Allicona Infinite Focus instrument and are equal to \( Ra = 0.282 \) μm and \( R_z = 7.71 \) μm. The samples for the tensile tests were cut in two orthogonal directions: along the rolling direction (0°) and transverse to the rolling direction (90°).

The friction coefficients of the sheets were determined by using the strip drawing test. The device for conducting this test is presented in Fig. 1. The details of the method and the simulator can be found in the previous papers of authors [2, 5]. The tests were done in such a way that a strip of the sheet was clamped with specified force between two fixed cylindrical rolls of equal radii of 20 mm.

| Table 1. Chemical composition of the main elements in tested sheets (% wt.) |
|-----------------|------|------|------|------|------|
| Ni              | Co   | Cr   | Ti   | Al   | Nb+(Ta) |
| 58 min.         | 1 max. | 20-23 | 0.40 max. | 0.40 max. | 3.15-4.15 |
| Mn              | 0.50 max. | 0.50 max. |
| Si              | 0.50 max. |

| Table 2. The selected mechanical properties and roughness parameters of the tested sheets |
|-----------------|-------|-------|-------|-------|
| Sample          | \( R_{p0.2} \) [MPa] | \( K \) [MPa] | \( n \) | \( r \) |
| orientation     |       |       |       |       |
| 0°              | 539   | 1936  | 0.345 | 0.654 |
| 90°             | 557   | 1846  | 0.321 | 0.941 |
The values of both forces, the clamping force $F_C$ and the pulling force $F_P$, were constantly recorded using electric resistance strain gauge technique. The samples were prepared as strips having 20 mm width and about 250 mm length, cut along rolling direction and transverse direction of the sheet. The three sets of rolls with different value of a roughness average $Ra$ (0.32, 0.63 and 1.25 μm) measured along generating line of rolls have been used in the strip drawing tests. The three friction conditions were considered: dry friction (unlubricated), and lubricated using two lubricants, i.e. machine oil L-AN 32 (O) and heavy-duty chlorinated honey-type stamping oil (HD). The pressure forces were in the range of 1000-2000 N.

3. Numerical modeling
The determination of the nominal area of contact is very difficult due to elastic-plastic character of deformation of roughness asperities at high pressures. The nominal areas of contact of the rolls with the sheet were evaluated using numerical modelling in MSC. Marc 2014 program. The sheet width is considerably higher than the sheet thickness, so it is assumed that the sample is drawn in plane strain conditions. The meshed model (Fig. 2) of the blank consists of 92000 elements, with 150 elements through the sheet thickness.
Figure 3. Variation of pressure force at the stage of roller indentation (I) and the stage of sheet pulling (II)

The blank was modeled with 4-node plane strain full integration elements quad-4. The surfaces of rolls were considered as rigid. The elastic behavior of the sheet metal is specified in the numerical model by the value of Young’s modulus, \( E = 205 \) GPa, and Poisson’s ratio \( \nu = 0.308 \). The material properties are assumed to be isotropic. The plastic properties of sheet material, including strain hardening phenomenon described by Hollomon law [12], were specified based on the mechanical parameters listed in Table 2. The contact between the roller surfaces and the workpiece was defined by the Coulomb friction model according to which frictional sliding force is proportional to the applied normal load. The specifications in the numerical model friction coefficient corresponds to the values in the experimental data. The calculations were performed using the implicit finite element code [13]. The advantage of this procedure is that the internal forces are balanced with the external forces through an iterative procedure. So, the deformed state can be determined after a time increment.

4. Results

As depicted in Fig. 4 (a) – (c), the friction coefficient value, in general, decreases with an increase of the pressure load, for all friction conditions, but mostly non-linear. This can be due to the fact that the relation between clamping force \( F_C \) and pulling force \( F_P \) is non-linear. In the case of roll roughness of 0.32 \( \mu m \) (Fig. 4a) the lubricant in the higher degree reduced the frictional resistances. The value of the friction coefficient in the case of lubrication by heavy-duty stamping oil is the most similar in the whole range on pressure force analyzed (Fig. 4a-c). Machine oil is the most effective in reduction of frictional resistances when using the roll with the lowest surface roughness (Fig. 4a). An increase of the surface roughness lowers the value of the dry friction coefficient. When machine oil is used, however, the high surface roughness of countersamples (Fig. 4b,c) leads to intensification of seizure of roughness asperities and the effectiveness of machine oil is smaller than in the case of tests realised using countersamples with surface roughness of \( Ra = 0.32 \mu m \) (Fig. 4a).

Based on the numerically predicted nominal area of contact, the nominal pressure was evaluated as the ratio of clamping force and nominal area of contact. The value of pressure force at sheet pulling stage is lower than the maximum force at the end of roll indentation stage. During sheet pulling the nominal area of contact is about two times smaller. However, the pressure force does not decrease proportionally due to the frictional resistances existed during sheet pulling (Fig. 3). The work hardening of the sheet material, which is characterized by high value of strain hardening coefficient \( K \) (Table 2), causes that near two-fold increase in the pressure load, i.e. from about 1 to 2 kN, influence the nominal pressure, up to 20% increase (Fig. 5). The plots in Fig. 5 also show that lubrication minimizes the difference in friction coefficient due to surface roughness differences. The lowest deviation is observed for heavy-oil lubrication.
5. Conclusions
In this article, experimental and numerical investigations were focused on to determine frictional resistances of AMS5599 nickel-based alloy sheets. The friction coefficient decreases with an increase of nominal pressure of rolls for all analyzed friction conditions. The coefficient of friction in lubricated conditions depends on mutual interrelation of supplying the lubricant to the contact area and flattening and roughening of surface roughness asperities of the sheet surface by roughness asperities of the tool surface. The hardness and strength of tool material are considerably higher than the sheet material. So, in contact interaction, the asperities of tool material will roughen the sheet surface. The preferred type of lubricant is heavy-duty stamping oil. In all analyzed friction conditions, this type of lubricant reduced the frictional resistance to the similar value of friction coefficient. The high strengthening of the sheet material causes that the relation between pressure force and area of contact is nonlinear.

6. References
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