Finite element method-based modeling of bending under tension friction test of deep drawing quality steel sheets

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Finite element method-based modeling of bending under tension friction test of deep drawing quality steel sheets

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Abstract. Understanding of the effect of the friction on the sheet deformation is a key factor in design and realization of stamping process. Among others, bending under tension friction test simulates the frictional phenomena on rounded edge of punch in sheet metal forming operations. In this paper, change of friction coefficient with 1-mm-thick deep drawing quality steel sheet deformation was evaluated using a special tribological simulator which simulates the friction in rounded edge of punch. The results of experimental investigations have been used to verify the results of numerical modeling carried out in MSC.Marc 2014 program. The friction coefficient value and contact stresses have been determined numerically. The results show that the distribution of the normal and friction stresses is very non-uniform along the wrap angle of the cylindrical countersample and along the specimen width. It has been concluded that FEM-based investigations allow a fast and suitable selection of the punch edge profile ensuring an increase of maximum allowable sheet strains.

1. Introduction

Sheet metal forming operations are characterized by different stress and strain state in the volume of drawpiece stamped. So, it is necessary to use different tests which reflect the frictional phenomena in specific areas of the workpiece. The tests simulating friction and lubrication conditions can be divided into tests simulating processes and tests simulating tribological conditions [1, 2]. The task of tests simulating processes is to model the plastic processing operations while maintaining the kinematics of the process. The tests simulating tribological conditions model a specific phenomenon, often without preserving the kinematics of the process. Both groups of tests can be divided into tests with direct or indirect measurement of the coefficient of friction. In the indirect friction determination methods, the coefficient of friction is determined based on the measurement of other quantities, such as friction force and normal force. Then, based on the adopted friction model, the friction coefficient is calculated [3]. Review of friction modeling in metal forming processes has been recently provided by Nielsen and Bay [4].

Due to the existence of differentiated conditions in individual areas of drawpiece in terms of stress, deformation and displacement speed, a series of tests modeling the friction conditions has been developed for sheet metal forming (Fig. 1). The basic tests modeling the friction conditions during sheet metal forming include:

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– strip drawing tests,
– bending under tension and draw bead tests,
– drawing and bending under tangential compression tests,
– hemispherical stretching,
– strip reduction tests.

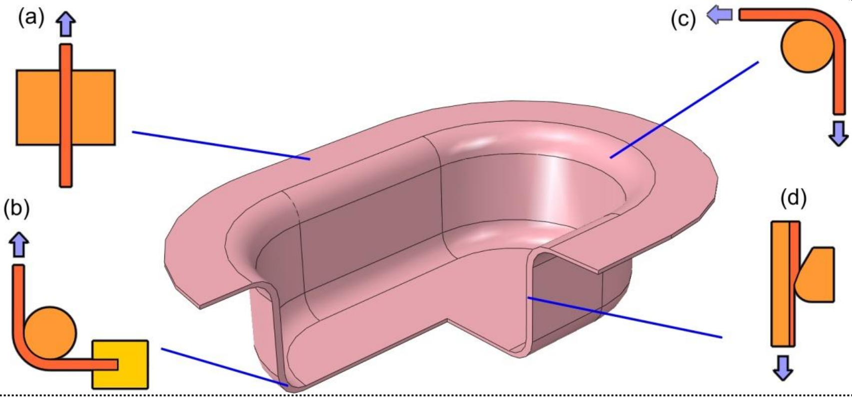

Figure 1. Basic types of friction tests and regions for which they are assigned: a) strip drawing test, b) bending under tension test of fixed sample, c) bending under tension test, d) strip reduction testing

The Bending Under Tension (BUT) developed by Littlewood and Wallace [5] represents the frictional flow of sheet material around a die or a punch radius. This test consists in drawing the strip of sheet metal around the cylindrical countersample. The BUT test allows to determine not only the value of the coefficient of friction, but also its change during the process of sample stretching [6, 7]. This change may be related to the change of the surface topography of the sheet because of deformation [8] and the change of contact conditions related to the strain hardening of the material, especially roughness asperities [9].

Due to the importance of the friction in metal forming, many researchers have devoted themselves to determination of the frictional conditions in the punch edge using both experimental and numerical methods. The BUT friction test method has received considerable interest for the evaluation of the frictional characteristics of coated sheet steel [10]. Different mathematical representations were used by Nanayakkara et al. [11] to determine the coefficient of friction in the BUT test. The effect of roller radius on friction was considerable and it was observed that there is a clear relationship between the contact pressure and the coefficient of friction. Andreasen et al. [12] developed a special BUT transducer in which friction around the tool radius can be directly measured. Hadoush et al. [13] analysed the continuous bending under the tension test by the numerical simulation. The sensitivity of the numerical model to mesh or discretization as well as the influence of different material models are studied. Lemu and Trzepieciński [14] studied the influence of lubrication condition and the variations of friction behavior with surface roughness. The experimental and numerical simulations has shown that it is possible to forecast the value and distribution of local deformations in real sheet metal forming operations. Ceron et al. [15] performed the finite element analysis of the evolution and distribution of temperature in the BUT test by using boundary conditions and calibration values directly measured from experiments. In a recent study, Trzepieciński and Lemu [16] proposed a new experimental-numerical method of friction determination on the rounded profiles of punch edges. The results of both experimental and numerical approaches confirmed the usefulness of the proposed method.

In this paper, change of friction coefficient of deep drawing quality steel sheet deformation was evaluated using special tribological simulator which simulates the friction in rounded edge of punch and die. The results of numerical modeling by finite element-based MSC.Marc program are verified by results of experimental investigations.

2. Experimental procedure

The frictional investigations have been carried out on 1-mm-thick deep drawing quality DC04 steel sheets. The mechanical properties determined through the uniaxial tensile test in the universal testing machine are listed in Table 1. The samples for the tensile tests were cut along the rolling direction (0°) and transverse to the rolling direction (90°). The surface roughness parameters of the tested sheets were measured using Taylor Hobson Surtronic 3+ profilometer at two orthogonal directions (0°, 90°) at specimen surface. The average surface roughness *Ra* and the total height of the roughness profile *Rt* are as follow: $Ra(0°) = 0.22$ µm, $Ra(90°) = 0.24$ µm, $Rt(0°) = 1.8$ µm,and $Rt(90°) = 3.5$ µm.

Table 1. The selected mechanical properties of the tested sheet

Sample orientation	Yield stress $R_{p0,2}$ [MPa]	Strain hardening coefficient K [MPa]	Strain hardening exponent n
0°	170	385	0.16
90°	160	369	0.15

The experiments were carried out using a special simulator of bending under a friction test shown in Fig. 2. A test strip with width of 10 mm was held at one end in a grip supported by a load cell. The specimen is wrapped around a cylindrical fixed roll with a diameter of 20 mm and loaded in a tensile testing machine ensuring contact over an angle of 90°. The test was carried out using rolls with different average surface roughness qualities Ra = 0.32, 0.63, 1.25 and 2.5 µm. The occurrence of frictional resistance between the sheet metal and roll causes that $F_1 > F_2$. The tensile forces F_1 and F_2 were measured simultaneously during the test and the value of friction coefficient (Fig. 3) was determined using formula shown in Fig. 2. The plots presented in Fig. 3 reveal that the change of friction coefficient value depends on surface roughness of the working roll. In all cases, the friction coefficient value increases with the specimen deformation and then this value is stabilized. An increasing of working roll surface causes an increase of the value of coefficient of friction.

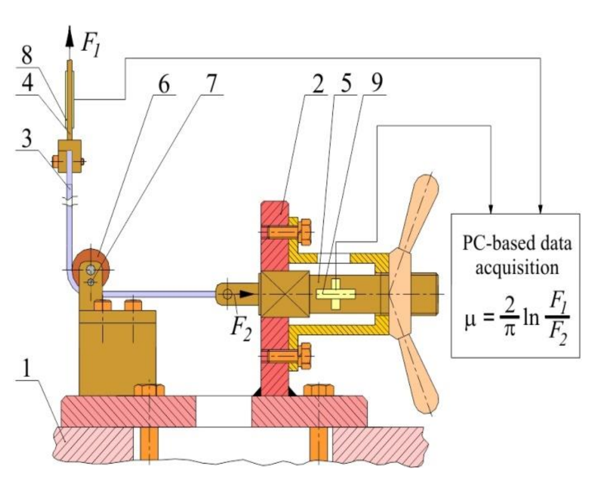

Figure 2. Schematic view of testing device; 1 – machine base, 2 – device frame, 3 – specimen, 4 and 5 – tension members, 6 – working roll, 7 - fixing pin, 8 and 9 – extensometer

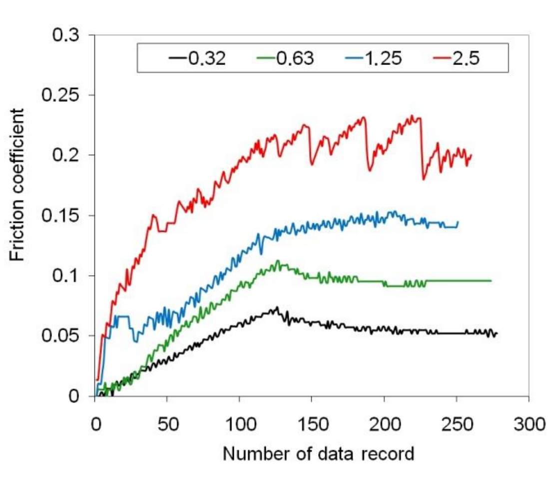

Figure 3. Effect of working roll roughness (µm) on the variation of coefficient of friction

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3. Numerical modeling

The numerical modelling of bending under tension test has been performed in MSC.Marc 2014 program. The roll was modeled as perfectly rigid, so only external surface represents the real geometry of the roll. The specimen was discretized using 3-dimensional eight-node, isoparametric arbitrary hexahedral elements and mesh is densified in the vicinity of contact the sheet metal with roll. The used element is preferred over higher-order elements when used in a contact analysis [17]. The meshed model of the specimen consists of 17040 elements, with 6 elements through the sheet thickness. The sheet material is considered to be elastic-plastic and isotropic. The elastic behavior of the sheet metal is specified in the numerical model by the value of Young's modulus, E = 210 GPa, and of Poisson's ratio ν = 0.3. The plastic properties of sheet material, including strain hardening phenomenon described parameters of Hollomon law (K and n) [18], were specified based on the average mechanical parameters determined for two orthogonal directions, listed in Table 1. Two simulations for friction and frictionless contact were carried out. In first model, the contact between the roller surface and the specimen was defined by the Coulomb friction model with a friction coefficient change corresponded to the approximation line of experimental results (Fig. 4). In the case of frictionless conditions "frictionless" option has been applied. Applied boundary conditions that allow measuring the tensile forces were applied to both ends of the sample. To enforce the intermittent contact and sliding boundary condition between the sheet and roll the penalty formulation for frictional contact was used. Calculations were performed using the implicit procedure where the internal forces were balanced with the external forces through an iterative procedure. To solve the Newton-Raphson's iterations, the time step was controlled by ABAQUS automatic incrimination technique. Double precision executable was used in the numerical analyses.

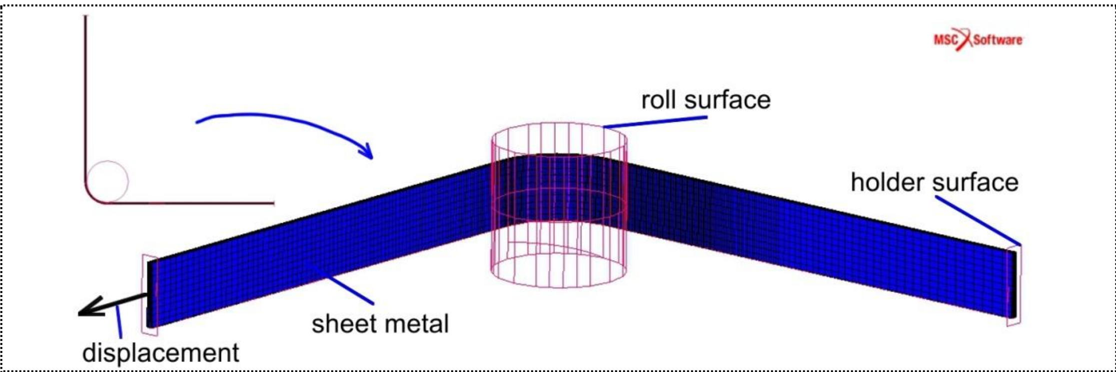

Figure 4. Finite element model of bending under tension friction test.

4. Results

Figure 4 shows the results of prediction of friction coefficient by numerical model. The error of FEM prediction of friction coefficient value does not exceed 0.03 and appears in the initial stage of BUT test. The initial deviation of the friction coefficient value at initial stage of BUT test is related to the elimination of the possible allowances of the device structure. So, the form of approximation function (black line in Fig. 5) is so selected to smooth the initial stage of the friction coefficient variation. The FEM model assumes ideal stiffness of the structure.

The distribution of the normal and friction stress is highly non-uniform along the wrap angle of the cylindrical countersample (Fig. 6). The maximum value of both aforementioned stresses is in the wrap angle of 5°. The most uniform distribution of contact stresses is in the range of wrap angle between 30 to 75°. The high resistance to friction causes that the most material effort exists in the vicinity of the exit of the specimen from the contact with countersample (at wrap angle of about 90°). This region is the most exposed to the fracture when the sheet deformation exceeds the allowable strain [19, 20].

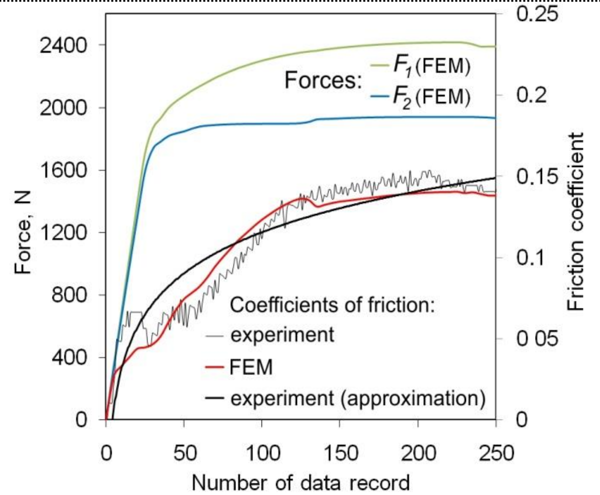

Figure 5. Variation of forces and friction coefficient value during the BUT test

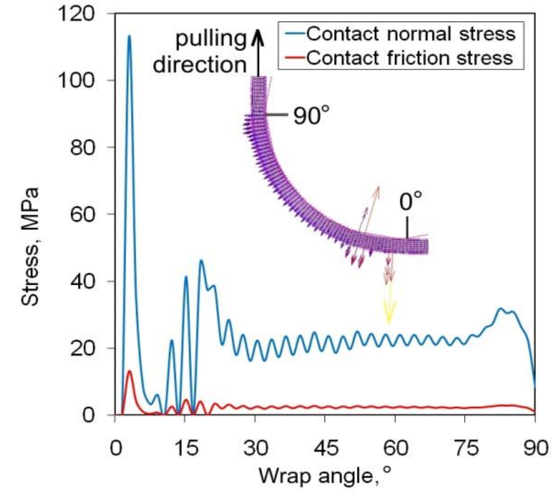

Figure 6. Variation of the contact normal and friction stress along the wrap angle

The contact normal stress changes both along the wrap angle and the specimen width (Fig. 7). The bending of the flat samples around the roll causes the specific stress state which led to deviation in the contact area. In the middle part of the sample width on the inner side, the longitudinal stresses are compressive and the deformation is negative, and on the external side, the longitudinal stress is negative and the deformation is positive. This phenomenon is however disturbed at the edge of the sheet and is discussed in the previous article of authors [21 - 22]. This is the clearly visible in the distribution of equivalent plastic strain in three selected cross-sections of the specimen, shown schematically in (Fig. 7). The deviation in the equivalent plastic strain (Fig. 8) causes changes in the adhesion of the specimen around the wrap angle of countersample. In this article, the punch with the rounded edge is considered. However, it can be speculated that by suitable selection of the punch profile, the maximum allowable specimen strain can be increased.

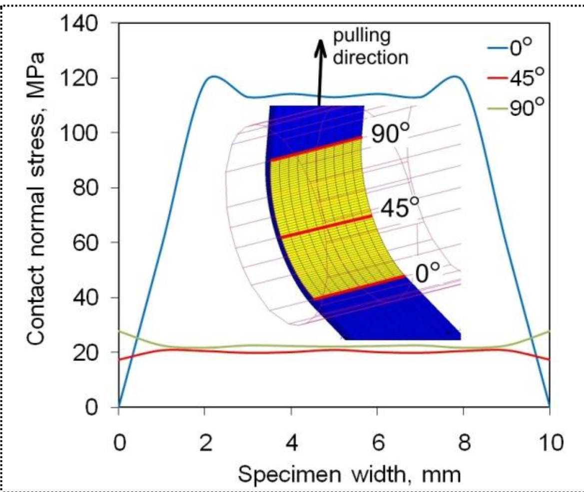

Figure 7. Variation of contact normal stress along the specimen width

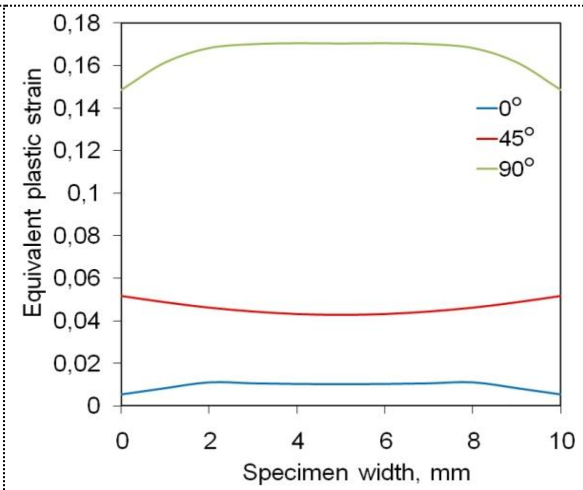

Figure 8. Variation of equivalent plastic strain along the specimen width

5. Conclusions

The experimental investigations of the friction phenomenon using bending under tension friction device shows that an increase of the roughness of the tool surface causes an increase of the value of coefficient of friction at the rounded edge of the punch. By application of the FEM, it is possible to simulate the sheet metal flow around the punch edge and prediction of the friction coefficient value. Furthermore, based on the numerical simulations results we can forecast the value and distribution of local deformations and contact stresses in the sheet metal forming processes.

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