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NUMERICAL ANALYSIS OF THE IRONING PROCESS UNDER CONDITIONS OF VARIABLE LATERAL FORCE

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Abstract: *In this paper, the ironing process is analyzed using the finite element method in the case where the lateral force is variable. Ironing with variable lateral force represents a tribological model of sheet metal sliding between two contact elements that perform sheet metal thinning. The results of the numerical analysis are compared with a real experiment and based on the comparison, conclusions are drawn as to which simulation parameters provide the best accuracy of the numerical simulation. The sheet metal strips are made of two materials, DC04 steel and brass, and two lubricants are used, mineral oil and* MoS_2*. The lateral and drawing force diagrams and sheet metal thickness are compared.*

Keywords: *finite element method, ironing, variable lateral force, mineral oil,* MoS_2

1. INTRODUCTION

Ironing is a process where a strip of sheet metal is thinned under the action of a lateral force. During the test, the sheet metal is subjected to a drawing force and a lateral force. The ironing test is a good way to evaluate the behavior of the sheet metal during deep drawing with thinning, as well as the influence of the lubricants used. There are two variants of ironing. In the first, the lateral force is constant, and in the second, it is variable. In this paper, the case where the value of the lateral force is variable is analyzed using numerical simulations, and in this way the thickness of the sheet metal is controlled. In industrial applications, deep drawing with thinning is used in the can manufacturing industry, the military industry, etc., so ironing is the subject of numerous studies. Currently, there is no possibility to apply the variable lateral force model to an industrial die, but from the aspect of scientific research and potential progress, this model is very interesting. The results obtained by numerical simulation were compared with experimental results. The agreement of the results shows that it is possible to correctly analyze this forming process using numerical methods.

The deep drawing process is influenced by various parameters. The most influential are the tool material, the roughness of the tool, the roughness of the punch, deformation degree, the lubricant used, the geometry of the tool, i.e. the angle of inclination of the die, and the strain rate. The success of the process is assessed based on the roughness of the sheet, the drawing force, the friction force, the coefficient of friction, tool wear, and the occurrence of galling on the workpiece. The friction force in the deep drawing process plays a significant role. The success of the process depends on the stress state of the workpiece. Due to high contact pressures, welding or sticking of the workpiece material (softer material) to the tool (harder material) can occur. In order to prevent these phenomena, it is very important to correctly select the tool material and the appropriate lubricant or coating to be used [1].

Numerous studies have been conducted in this area. An experimental-numerical analysis of the influence of contact conditions on the ironing process is presented in [2]. The influence of four types of lubricants on the ironing process was analyzed and the results obtained experimentally and numerically were compared. The ironing process was carried out with constant lateral force values of 15kN and 20kN. It was concluded that under conditions of constant lateral force it is possible to adequately simulate the ironing process.

The aim of this research is to compare the experimental values of the lateral and drawing forces during the ironing test with the numerical values for two types of materials and two types of lubricants used. Based on the experimentally determined friction conditions, the tribological conditions were defined in the numerical simulation and the stress state of the sheet strip was analyzed. In addition to the values of the lateral and drawing forces, the sheet thickness will also be considered. Based on the results, it will be concluded whether it is possible to control the sheet thickness by controlling the lateral force during the ironing process. The study of the control of the lateral force and sheet thickness is significant in a theoretical sense as a possibility of potential use in the drawing process with thinning. The basics of ironing with variable lateral force are presented in the papers [3] and [4].

2. TEST MODEL

The results of the experimental part are presented in the paper [5]. In the aforementioned paper, a mechanical mathematical model of thinning of a sheet of greater thickness by the action of lateral force on both sides of the sheet is presented. The ironing model that was considered is shown in Figure 1.

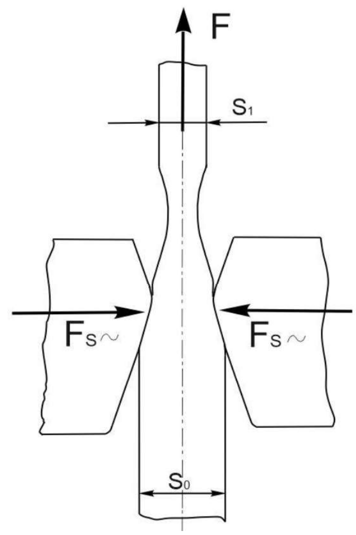


Figure 1. Scheme of the ironing process [5]

The samples were made of DC04 steel and CuZn75 brass. The dimensions of the test strip were 300x20x3 mm. Two types of lubricants were used: deep drawing oil (with steel) and M_oS_2 grease (with brass). The sliding speed was 20 mm/min and the sliding length was 60 mm. The tool drawing is shown in Figure 2 and the appearance of the dies prepared in the Simufact.forming software is shown in Figure 3.

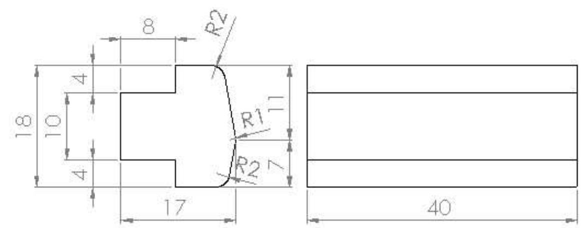


Figure 2. Drawing of the tool

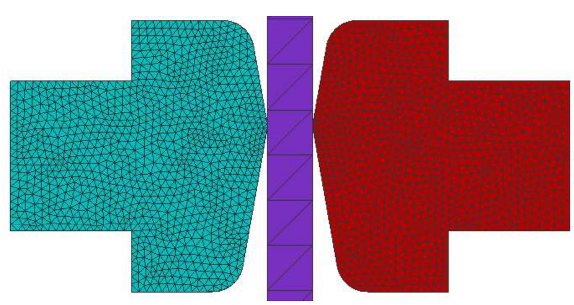


Figure 3. Tools and workpiece prepared for simulation

The flow curves of both materials were determined by uniaxial tensile testing. The friction conditions were taken from the experimental part.

2.1 Numerical simulation

To create the mesh on the sheet metal, the Quadtree mesher with the element type Quads, plane strain 11 was used. The element size was 0.3 mm and 10,000 elements were used.
The tensile test of the material was performed on a Zwick/Roell Z100 material testing machine. Based on the stress-strain diagram, a flow curve was created and analytical approximations of the two materials were determined using the least squares method. The tensile strength of steel is about 280 MPa and that of brass is 412 MPa. A representation of the flow curves of the two materials used is shown in Figure 4.

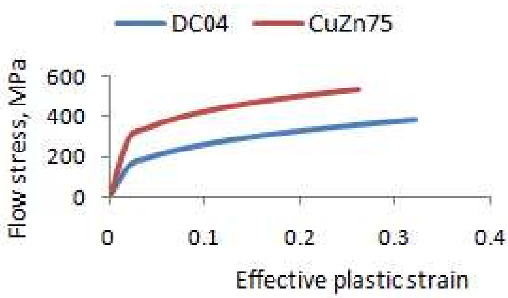


Figure 4. The flow curves

Tribological conditions are defined by the value of the coefficient/factor of friction as presented in [5]. According to the model used in this work, the coefficient of friction is calculated according to the formula:

$$\mu = \frac{F}{0.17101F + 1.357785F_S + 0.6F_S} . \quad (1)$$

In the case where steel strips were used, the friction coefficient value was from 0.25 to 0.5. In the case where brass and molybdenum disulfide strips were used, the friction coefficient value was from 0.2 to 0.5. Based on these experimental values, the friction model and the value of the factor /coefficient were defined.

2.2 Experiment plan

Since the ironing process is very complex, it is of great importance to determine which friction model is most suitable for use. There are several friction models in the Simufact.forming software: Coulomb's law, constant (shear) friction law, and mixed friction law. Coulomb's law of friction is used when the contact stress value does not reach the yield stress. The constant friction law is used when the contact stress values are greater than the yield stress. The combined or mixed friction law uses Coulomb's law in cases where the contact stress value is small, and for higher contact stress values, it uses the constant friction law. The final result of this research should be the answer to the question of which friction model is most suitable for use in numerical simulation of the ironing process with variable lateral force.

Based on the results from [5], the values of the coefficient/friction factor were determined as shown in Table 1.

Table 1. Friction coefficient/factor values

Material	Friction laws		
	Coulomb	Constant	Combined
DC04	μ=0,25	m=0,43	μ=0,25 m=0,43
CuZn75	μ=0,21	m=0,37	μ=0,21 m=0,37

3. RESULTS OF THE NUMERICAL EXPERIMENT

The process in the numerical experiment is shown in Figure 5. The sheet metal and dies are shown, and the values of the effective plastic deformation are visible on the sheet metal.

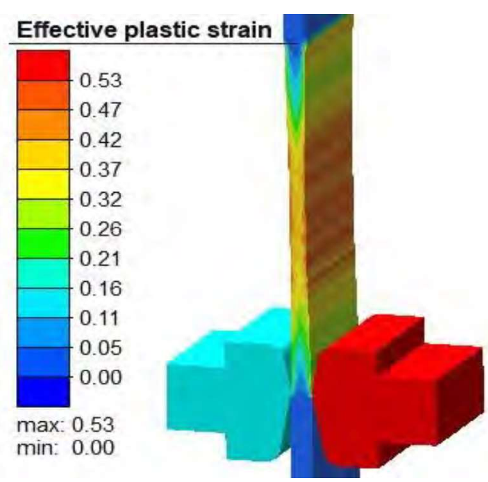


Figure 5. Effective plastic strain at the end of ironig process

The value of the effective stress on the sheet metal is shown in figure 6. Analyzing the stress values obtained by simulation, the conclusion is that the process was successful, that is, there was no fracture or tearing of the material.

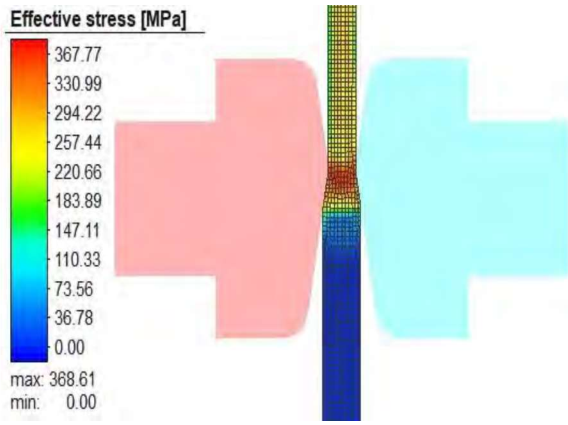
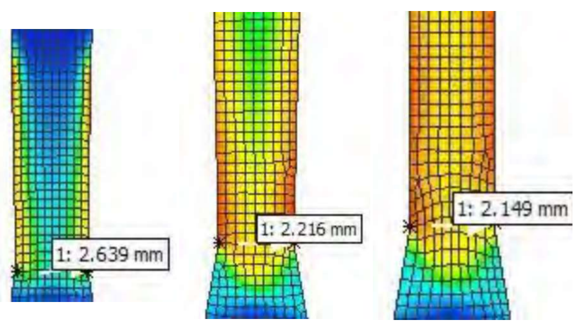
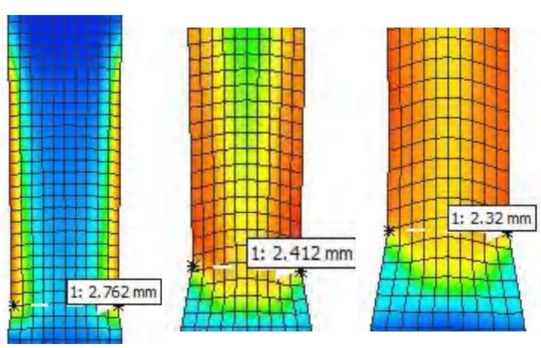


Figure 6. Effective stress distribution (DC04)

The sheet thickness distribution for both cases is shown in Figure 7. Figure 7 a) shows the sheet thicknesses of DC04 steel and b) of CuZn75 brass.



a)



b)

Figure 7. Sheet thickness after 10 mm, 20 mm and 30 mm of drawing length for a) DC04 b) CuZn75

The sheet thickness values shown in Figure 7 are satisfactory. Deviations are shown in Table 2.

Table 2. Sheet thickness deviations

	Exp. value, mm	Sim. value, mm	Deviation, %
DC04-10mm	2,63	2,639	0,34
DC04-20mm	2,19	2,216	1,19
DC04-30mm	2,12	2,149	1,37
CuZn75-10mm	2,77	2,762	0,29
CuZn75-20mm	2,37	2,412	1,77
CuZn75-30mm	2,27	2,32	2,2

Since the aim of the paper is to determine whether it is possible to adequately predict the behavior of the material during the ironing process using numerical simulations and which of the friction laws gives the best results, the analysis of the values of the drawing and lateral force is of great importance. A comparison of the drawing force of the DC04 sheet metal obtained experimentally and numerically using the three friction laws is shown in Figure 8. The best match of the traction force for the steel sheet was achieved for the constant friction law. The lateral force diagram of steel sheet ironing is shown in Figure 9. A better match of the maximum value of the lateral force was achieved for the Coulomb and mixed friction laws, while in the simulation where the law of constant friction was used, the deviation is slightly larger.

Figure 10 shows the drawing force diagram of the CuZn75 sheet ironing process. There is a significant deviation between the experimental and numerical results. During the experiment, some deviations obviously occurred in the second part of the experiment. The best match for maximum force value was achieved using the law of constant friction.

The ironing process and the equipment used are very complex, so it is realistic that the experimental results have certain deviations. This explains why the results obtained numerically cannot fully match those obtained experimentally. It is important to compare the maximum values of the drawing and lateral forces and calculate the deviations. The maximum values of the drawing and lateral forces for the steel ironing process obtained experimentally and numerically are shown in table 3.

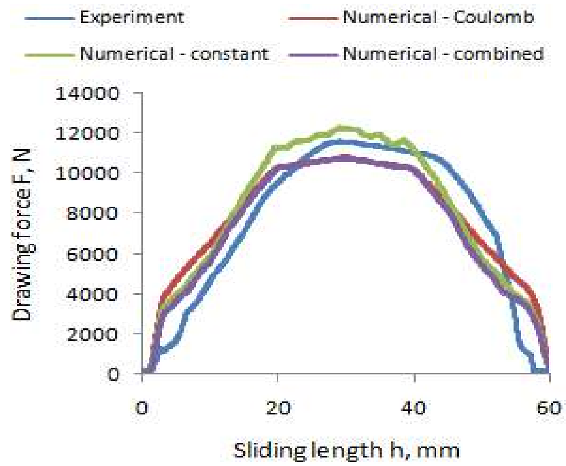


Figure 8. Drawing force diagram for DC04 material sheet strips

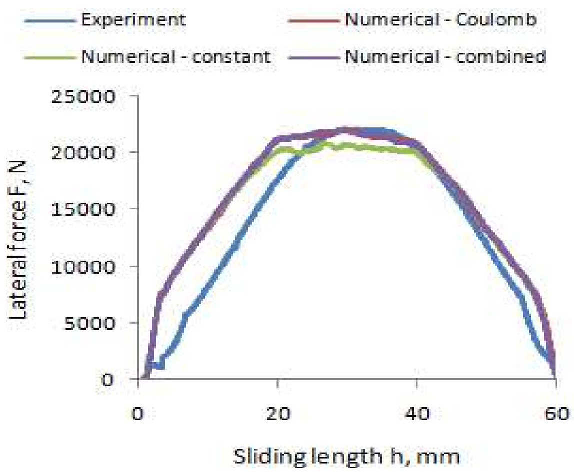


Figure 9. Lateral force diagram for DC04 material sheet strips

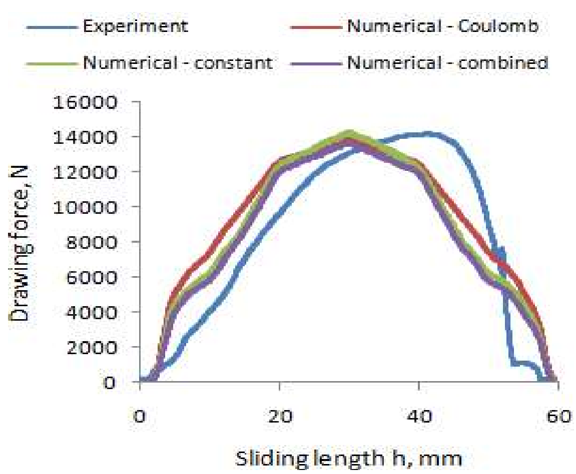


Figure 10. Drawing force diagram for CuZn75 material sheet strips

The lateral force diagram for CuZn75 sheet is shown in Figure 11.

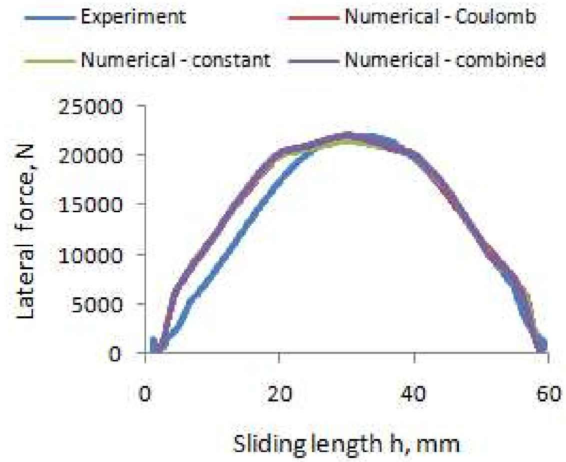


Figure 11. Lateral force diagram for CuZn75 material sheet strips

Table 3. Deviations of force values for steel DC04

	Drawing force, N	Lateral force, N
Experimental	11600,61	22130
Numerical - Coulomb	10843 (-6,53%)	22119,4 (-0,05%)
Numerical – constant	12312,2 (+6,13%)	20862,7 (-5,73%)
Numerical - combined	10751,2 (-7,32%)	22018,9 (-0,5%)

The results shown in Table 3 show that there are significant deviations between the experimental and numerical results, but that they are still within the ±10% deviation range that is acceptable for numerical analysis. In the case of drawing force, the smallest deviation is for the constant (shear) friction model, where the force value obtained numerically is slightly higher. For the other two models, the force value is lower than the experimental one and the results are similar, the deviations are -6.53% and -7.32%. In the case of lateral force, the best match is achieved for the Coulomb friction model, where almost identical values are achieved with a small deviation of -0.05%. The deviation of the force value is also very small for the combined friction model (-0.5%), while for the constant model it is slightly higher and amounts to -5.73%.

The results for the ironing process for brass samples are shown in Table 4.

Table 4. Force value deviations for brass CuZn75

	Drawing force, N	Lateral force, N
Experimental	14192,6	22060
Numerical - Coulomb	13881 (-2,2%)	22079,6 (+0,08%)
Numerical – constant	14280,9 (+5,92%)	21556,5 (-2,28%)
Numerical - combined	13657,1 (-3,77%)	22125 (+0,29%)

As in the case of the experimental results with steel samples, deviations exist but are within acceptable limits. For the drawing force, the smallest deviation is for the Coulomb friction model and amounts to -2.2%, followed by the combined -3.77% and the constant friction model with a deviation of +5.92%.

4. CONCLUSION

Based on the comparison and analysis of the experimental and numerical results, it is concluded that the ironing process can be correctly predicted using numerical simulations. By matching the sheet thickness, the values of the drawing and lateral forces, the model of controlling the sheet thickness by controlling the lateral force values is justified. Using all three friction laws in numerical simulations, similar results were obtained, so it was concluded that when simulating the ironing process, the choice of friction law does not have a decisive influence.

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