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AN EXPERIMENTAL MODELLING AND NUMERICAL FE ANALYSIS OF STEEL-STRIP IRONING PROCESS

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Original scientific paper

This paper deals with analysis of steel strip ironing using experimental modelling and numerical FE simulation. Since both approaches are complementary to each other, numerous results were obtained that enable complete analysis of the processes within deformation zone. Device for modelling of strip ironing has been developed for experimental testing. Die cone angle, holding force, contact friction conditions on the die and the punch side were varied, due to easily replaceable working elements of the device. Friction coefficient values used in numerical FE simulations were determined based on measured values of forces on die and punch, as well as forming load on machine. Experimentally obtained results were confirmed by FE analysis that provided additional information about physics of the process itself within deformation zone. Presented research results point to coherent influences of process factors on tensile wall stress values, which represents key indicator for efficiency of forming, resulting in recommendations for efficient process management.

Keywords: *FE numerical simulation, modelling, steel strip ironing, wall stress*

Eksperimentalno modeliranje i numerička FE analiza procesa izvlačenja sa stanjenjem čeličnih traka

Izvorni znanstveni članak

Rad se bavi analizom procesa izvlačenja sa stanjenjem čelične trake, primjenom eksperimentalnog modeliranja i numeričkih FE simulacija. Kako su oba pristupa komplementarna, dobiveno je mnoštvo rezultata za sveobuhvatnu analizu procesa u deformacijskoj zoni. Za potrebe eksperimentalnog modeliranja razvijen je uređaj za modeliranje procesa izvlačenja sa stanjenjem trake. Zahvaljujući lako izmjenjivim radnim elementima uređaja, varirane su vrijednosti kuta matrice, sile držanja, uvjeti kontaktnog trenja na strani izvlakača i matrice. Vrijednosti faktora trenja, korištenih u numeričkim FE simulacijama su određene na osnovu izmjerenih vrijednosti sila na matrici i izvlakaču, kao i ukupne sile na stroju. Eksperimentalno dobiveni rezultati potvrđeni su numeričkom FE analizom, pri čemu je ona dala dodatne informacije o samoj fizici procesa u deformacijskoj zoni. Prikazani rezultati istraživanja ukazuju na spregnute utjecaje analiziranih faktora procesa na iznos rasteznog naprezanja u stijenki matrice, koji predstavlja ključni pokazatelj uspješnosti obrade, iz kojih proizlaze preporuke za uspješno upravljanje procesom.

Ključne riječi: *duboko izvlačenje sa stanjenjem debljine stijenki, FE numerička simulacija, modeliranje, naprezanje u stijenki*

1 Introduction
Uvod

The process of producing the parts by ironing is strongly influenced by a large number of factors. All of them can be divided into four groups:
- influential factors that depend on the contact conditions (tribological conditions)
- influential factors that depend on the workpiece (material, dimensions and shape)
- influential factors that depend on the tool
- influential factors that depend on the machine.

By taking into account the forming process and all the influential factors of all the elements that are taking part in it, the targeting of the investigation direction can be done, in order to optimize the forming process both from the aspect of the workpiece quality and the aspect of increasing the productivity and lowering the manufacturing costs.

It is clear that the influence of tribological conditions at ironing is extremely important and it has been the subject of researches of many researchers during the past years, both in real processes and on models. The investigation of tribological conditions takes much more time and is considerably more expensive. Investigations on models are more often practiced. Modelling of tribological conditions implies the satisfying of the minimum of necessary criteria, with regard to similarity in: stress-strain relationship, temperature-velocity conditions, properties of tool and material surface and their contact during the process.

It is possible to find in literature the whole series of models which were mainly developed for particular purposes.

Tribo test developed by J. L. Andreasen and N. Bay [1] was used for simulation of tribological conditions of ironing process. Sheet strip is ironed between non-rotating pin (presser) that simulates the die and prismatic carrier that simulates the punch. Influence of the reduction rate, sliding speed and tool temperature over the sliding path during which galling occurs, can be investigated by this test, using different lubricants.

Tribo-model developed by N. Kawai [2] with his associates enables investigation of influence of various factor changes, such as: tool material, die cone angle, sliding path, sliding speed, die and punch roughness etc, and their influence on "cold welding" processes, as well as on the quality of obtained surfaces during the ironing. Friction force, i.e. friction coefficient on the punch side cannot be measured at this device, what certainly is disadvantage of this device.

Model suggested by Schlosser [3] anticipates sliding of the sheet metal strip between two specially made pressers simulating the tool. Contact surfaces are inclined under the angle to the direction of the sheet motion. This method is mainly applied for the evaluation of lubricant suitability aimed for working at processing with high contact pressures.

Tribo model developed by Deneuville and Lecot [4], enables sheet metal strip ironing using movable die, while punch is stationary, what does not correspond to the real conditions – movable punch and stationary die. Based on measured values, it is possible to calculate friction coefficient on the die and the punch side.

The mutual property of all models is that they do not completely imitate the real process of ironing regarding tool geometry, stress-strain state or contact state during forming. For most of the illustrated models it is not possible to determine the friction force, i.e. coefficient of friction between workpeace and punch, which has the extreme importance in the ironing process. Also, for most of the models, the angle of die cone is not taken into consideration. For this reason the suggested models have limited application, which should be taken into consideration.

Taking into account the advantages and disadvantages of the specified models and taking into consideration the experimental possibilities, in this paper we have proposed one new model of ironing, that is a device for physical modelling of strip ironing, which imitates the zone of contact between die and punch, as double-sided and symmetrically. This model allows the realization of high contact pressures and takes into account physical and geometrical conditions of the real process (material of die and punch, topography of contact surfaces, angle of die cone etc.) [5].

The wall ironing process has been studied using combined experimental and numerical approach in many researches. Van der Aa at al [6] applied both techniques for analysis of the ironing process of polymer coated aluminium and steel sheets. They developed plane strain strip ironing device in order to investigate the influence of the ironing reduction, velocity and die angle on the process forces and friction. FE simulations of the process have been performed using an arbitrary Lagrange. Experimentally obtained friction coefficients were directly used in numerical simulations. Experiments and numerical simulation have proved to be complementary.

Schunemann, Ahmetoglu and Altan [7] simulated drawing, redrawing and ironing process of aluminium sheet using DEFORM, as rigid-plastic explicit FE code. More fundamental and practical aspects of aforementioned processes were investigated, such as: thickness reduction, wall stress, prediction of punch forces, temperature distribution etc. Numerical results are comparable with experimental, used from literature.

Usage of program for numerical simulation and physical modelling techniques are complementary, due to their advantages and restrictions. The application of these methods represents the new concept in designing of processes and tools, for comprehensive analysis of different bulk metal forming processes Mandic [8]. The similar approach of physical-numerical modelling of real processes in laboratory conditions was also applied in investigation of ironing process. Mandic at all [9] used strip ironing device which enables the monitoring of coupled influence of process parameters (die angle, friction conditions, workpiece and tool material etc.) on process outputs in form of material flow, wall stress changes and forming loads. Numerical analysis verified experimental results offering deep understanding of physics of process.

The use of this new concept in designing and investigation of processes has significantly increased, especially during the last ten years, in research and development activities, in academic institutions and development laboratories of the companies. The efficiency of such concept is reflected through many advantages for designers and researchers.

2 Theoretical survey
Teorijska istraživanja

It is characteristic that at ironing process high normal stresses appear at contact surfaces as well as different

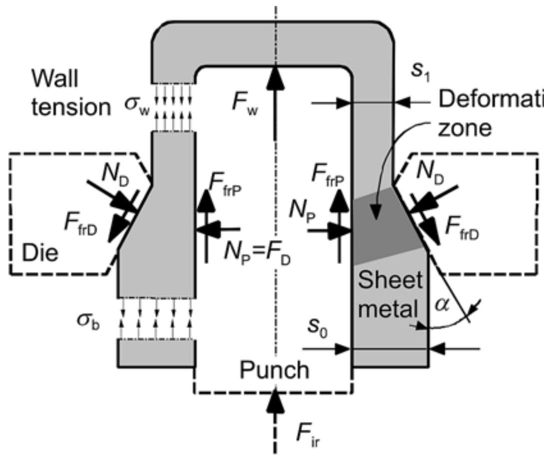


Figure 1 *Scheme of the forces action on the sheet*
Slika 1. *Shema delovanja sila na traku lima*

directions of the friction forces that act at the external and internal sides of the workpiece. The friction forces directions are opposite because the piece is moving through the die during ironing, and thus the friction force at the external surface has the direction opposite that of the ironing. At the same time, due to ironing, the workpiece is being extended, thus the friction force at the internal surface of the piece will be directed in the sense of drawing (Fig. 1).

The ironing is conducted in conditions of the three dimensional strain scheme, where all the three main strains are, in general case, different from zero. However, without gross error, one can consider that the ironing is conducted in the plane strain conditions, where the two main strains represent: the compressive strain in the radial direction (decrease of thickness) and strain in the extension axis direction (increase of the workpiece's length). The strain in the tangential direction can be considered to be zero, since the clearance between the punch and the die is usually small with respect to the punch diameter. In those conditions, the tangential strain is equal to zero at the internal surface of the workpiece and it reaches the maximal value at the external surface of the workpiece, which is in ironing usually very close to zero [10].

Due to the fact that ironing is conducted in the conditions close to the plane strain, it follows that the tangential stress is equal to the half of the sum of the axial and radial stresses. The scheme of the external forces and the character of the forming enable the conclusion that the axial stress is tensile, while the radial stress is compressive.

Considering that ironing is usually done in conditions of the good lubrication ($\mu < 0,2$) and that normal stresses at the contact surfaces do not exceed the yield stress, the magnitude of the shear stresses at the contact surface should be significantly smaller than k (the shear strain resistance). Various directions of the friction forces on contact surfaces of the punch and die enable the assumption that the shear stresses in the radial direction are almost constant.

Force F_z, which acts on the bottom of the piece, causes the appearance of the tensile stresses in the workpiece wall, both in the ironed portion and in the deformation zone. Those tensile stresses have the maximal value at the exit of the workpiece from the die and they are decreasing to certain minimal value, which they have at the entrance of the workpiece in the deformation zone. The minimal value of the stress at the entrance part of the die (σ_b) can be [11]:

- equal to zero ($\sigma_b = 0$), if the ironing is done with one die,
- greater than zero ($\sigma_b > 0$), if the ironing is done through several dies and then that value of stress is equal to

maximal value of the wall tensile stress at the exit from the previous die and

- less than zero ($\sigma_b < 0$), if the workpiece is being pushed in from the back side.

The wall tensile stress in the ironed portion of the workpiece, besides other, depends on the tribological conditions on the contact surfaces between the punch and die at one side and the workpiece at the other side.

Based on the analysis of the stress state of the ironing process by slab method, one comes up with the following equation for the stress in the workpiece wall at the exit from the die [12]:

$$\sigma_w = \frac{1}{A-1} \cdot \left\{ \begin{array}{l} \left(\frac{s_1}{s_0}\right)^{A-1} \cdot \left[\begin{array}{l} \sigma_b \cdot (A-1) - \\ \frac{2}{\sqrt{3}} \cdot k \cdot A \end{array} \right] + \\ + \frac{2}{\sqrt{3}} \cdot k \cdot A \end{array} \right\} \cdot \left(1 - \frac{\pi \cdot \mu_D \cdot D_1}{s_1} \cdot L\right) + \frac{2}{\sqrt{3}} \cdot \frac{\pi \cdot \mu_D \cdot D_1}{s_1} \cdot L, \quad (1)$$

where:

$$A = \frac{1}{\cos\alpha} + \frac{\mu_D}{\sin\alpha} - \frac{\mu_P \cdot n}{\tan\alpha}. \quad (2)$$

In equation (1) the elements of coefficient A have the defined physical meaning. The first part of coefficient A, $1/\cos\alpha$, characterizes the resistance to forming in ideal ironing conditions (without the friction at contact surfaces); the second part, $\mu_D/\sin\alpha$, represents the influence of friction on the die side; and the third part, $\mu_P \cdot n/\tan\alpha$, represents the influence of friction on the punch side. The friction coefficients on the punch and the die sides are different from each other due to difference in materials and quality of punch and die surfaces.

If the friction coefficient on the die side (μ_D) is different from the friction coefficient on the punch side (μ_P), then by adequate ratios of those coefficients one can influence the value of the tensile stress σ_w. By that, as follows from equation (1), at $A = 1$ stress σ_w corresponds to ideal ironing process; at $\frac{1}{\cos\alpha} + \frac{\mu_D}{\sin\alpha} = \frac{\mu_P \cdot n}{\tan\alpha}$, stress is $\sigma_w = 0$, while at $\frac{1}{\cos\alpha} + \frac{\mu_D}{\sin\alpha} < \frac{\mu_P \cdot n}{\tan\alpha}$, stress σ_w reverses sign and becomes compressive (caused by the increased friction force at the punch).

Influence on the magnitude of σ_w, by significant increase of the friction coefficient μ_P is practically forbidden, because in that case the persistence of the punch is significantly decreased.

From the formula for determination of the coefficient A follows that it does not depend only on values of the friction coefficients on the contact surfaces, but also on the value of the semi angle the die cone (α).

The total drawing force F_{ir} represents the sum of the friction force between the punch and the workpiece, F_{frP} and the force that acts on the bottom of the strip, F_w:

$$F_{ir} = F_{frP} + F_w. \quad (3)$$

The F_{ir} force is being measured on the machine itself, while the friction force F_{frP} is being registered by the pick-up with strain gauges.

From the previous equation (3) follows that:

$$F_w = F_{ir} - F_{frP}. \quad (4)$$

The force F_w, which acts on the bottom of the strip causes in the strip walls the stress σ_w, which can be calculated based on the following expression:

$$\sigma_w = \frac{F_w}{2 \cdot b \cdot s_1}, \quad (5)$$

where:
b is the sample thickness,
s_1 is the strip thickness after ironing.

The friction coefficient on the punch side, taking into account that it changes according to Coulomb's law, can be calculated from the expression:

$$\mu_P = \frac{F_{frP}}{2 \cdot F_D}, \quad (6)$$

and the friction coefficient on the die side can be calculated as:

$$\mu_D = \frac{F \cdot \cos\alpha - 2 \cdot F_D \cdot \sin\alpha}{F \cdot \sin\alpha + F_D \cdot \cos\alpha}. \quad (7)$$

Knowing the dependence of forces F_{ir} and F_{frP} on the sliding path h, it is possible, based on the previous expressions, to calculate the friction coefficients (μ_D and μ_P) in terms of the sliding path.

3 Experimental investigations
Eksperimentalno istraživanje

3.1 Description of equipment and tool
Opis opreme i alata

Experimental investigations in this paper were conducted on the original model of ironing, which double sided simulates the contact zone with the punch and die [5]. This model enables realization of the high contact pressures and respects the physical and geometrical conditions of the real process (die and punch materials, topography of the contact surfaces, the die cone angle α etc.). The scheme of the mentioned model is shown in Fig. 2.

The dies are placed in holders, where the left hand holder is fixed and the right hand holder is moving together with the die. The punch consists of the body 3 and the front 4, which are mutually connected by the pickup with the strain gauges 5.

Shape of sheet strip is shown in Fig. 3, before and after bending, and final dimensions of test-piece, too. The bent strip of thin sheet 7, in the U-shape (test-piece) is being placed on the "punch". The strip is being acted upon by "dies" 2 with force F_D. Test-piece is passing (sliding) between dies, by the action of the force F_{ir} on the punch

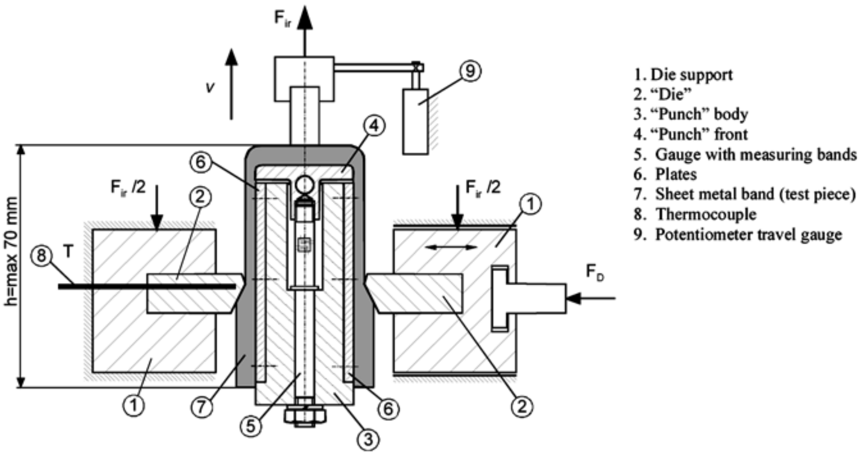
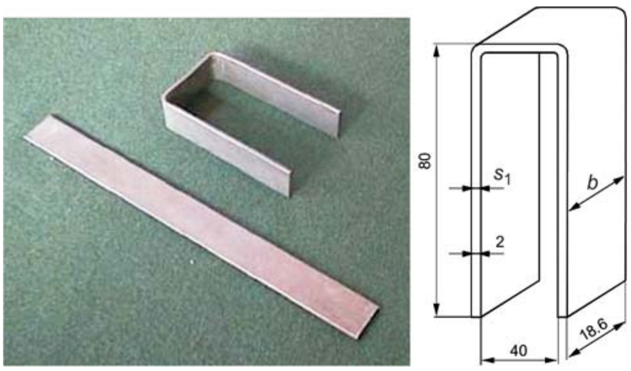


Figure 2 *Scheme of device for modelling of the ironing process*
Slika 2. *Shema uređaja za modeliranje procesa izvlačenja sa stanjenjem*

front, when the sample wall is being ironed. During passing through, the external surface of the sample is sliding along the die surface, which is inclined for an angle α, while the internal surface of the sample is sliding over the plates 6, which are fixed to the punch body.

The device was made with the possibility for an easy substitution of the contact – pressure elements (die 2 and plates 6), easy cleaning of the contact zones and convenient placing of samples.



a) b)

Figure 3 *Shape (a) and dimension (b) of test-piece*
Slika 3. *Oblik (a) i dimenzije (b) epruvete*

Plates 6 (see Fig. 4) and dies 2 (Fig. 5) can be made of various materials, as well as with various roughnesses, while dies can have various slope angle α.

On the mentioned device it is also possible to simulate consecutive (multi-phase) ironing, when one sample passes between the contact pairs several times.

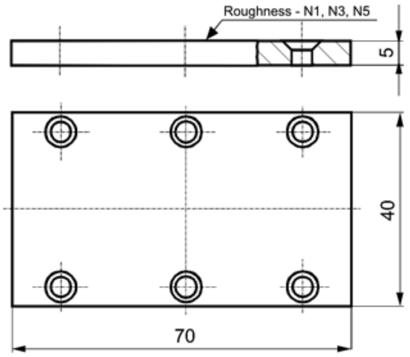


Figure 4 *Geometry of plates*
Slika 4. *Geometrija pločica*

The device for ironing is installed on a special machine for thin sheet testing ERICHSEN 142/12.

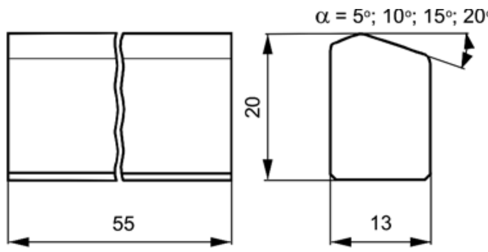


Figure 5 *Die geometry*
Slika 5. *Geometrija matrice*

3.2 Characteristics of used materials
Karakteristike korištenih materijala

For experimental investigations in this paper was chosen the low carbon steel sheet, tempered by aluminum, Č0148P3 (WN: 1.0336; DIN: DC 04 G1/Ust 4, Ust 14). It belongs into a group of high quality sheets aimed for the deep drawing and it has properties prescribed by standard SRPS EN 10130:2004.

For the die and punch material was selected the alloyed tool steel (TS) Č4750 (WN: 1.2601; DIN17006: X165CrMoV12; EN: X 160 CrMoV 12 1), while one set of dies was made of the hard metal. In order to improve the surface, both of a certain number of dies and of punches, their working surfaces were coated by chromium (Cr) or titanium nitride (TiN). In experiments were always used pairs of dies and punches made of the same materials, e.g., D-TS/P-DS or D-TS+Cr/P-TS+Cr, with exception of the hard metal die, which was always used with the punch made of tool steel.

Special attention was devoted to material characteristics in the sheet rolling direction (0°), since the tested samples were cut in that way. (SRPS C.A4.002:1986) which was applied using specimens in rolling direction, material characteristics for test-piece were determined. Values are shown in Tab. 1. Tests have been performed under laboratory conditions (v = 20 mm/min, ϑ=20 °C).

Experimentally obtained data for true stress - true strain relationship, that is flow curve, were fitted in exponential form. Eq. (8) was finally used for further numerical description of material flow and behaviour during FE ironing simulation, where K is true stress and φ is true strain.

***Table 1** Properties of tools and test piece materials*
***Tablica 1.** Osobine materijala alata i epruvete*

		Material	Mechanical properties
Tool	Die (D)	TS* TS + Cr plate TS + TiN plate HM**	TS Hardness 60÷63 HRC HM Hardness 1200 HV30
	Punch plate (P)	TS* TS + Cr plate TS – TiN plate * - TS – Tool steel, Č4750 (DIN17006: X165CrMoV12)	
Test-piece		Č0148P3 (WN: 1.0336; DIN: DC 04 G1/Ust 4) Thickness: 2,0 mm width: 18,6 mm	R_p = 186,2 MPa R_m = 283,4 MPa A_{80} = 37,3 % n = 0,2186, r = 1,31915
* - TS – Tool steel, Č4750 (DIN17006: X165CrMoV12) ** - HM – Hard metal, WG30 (DIN4990: G30)			

In Fig. 6 the flow curve is shown for the tested material in the rolling direction, obtained according to Eq. (8).

$$K = 491{,}6874 \cdot \varphi^{0{,}2186}. \qquad (8)$$

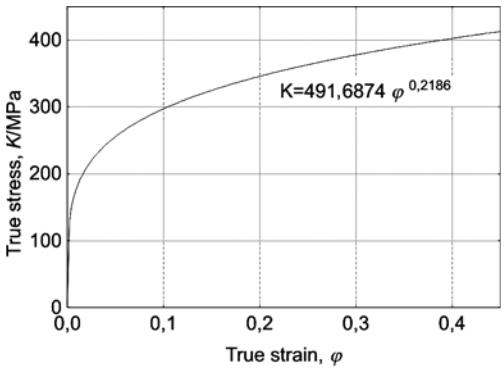


***Figure 6** The flow curve in the rolling direction (0°) of Č0148P3*
***Slika 6.** Krivulja ojačanja u pravcu valjanja (0°) lima za Č0148P3*

3.3 Conditions of ironing process
Uvjeti procesa izvlačenja sa stanjenjem

The die surface was polished in quality N1 (*Ra*≈0,01 μm), while the punch surfaces were produced with three different qualities: N1 - *Ra*≈0,01 μm, N3 - *Ra*≈0,09 μm and N5 - *Ra*≈0,4 μm. The rough punch surface (*Ra*≈0,4 μm) was chosen in order to obtain the value of the friction coefficient on the punch side as high as possible.

All the investigations were performed at the room temperature, with the ram speed of 20 mm/min and the punch stroke of maximum 70 mm. The reduction degree was between 1 % and 55 % and was realized by various values of the holding force F_D.

Considering that the forming processes are very different and that they have wide area of process realization parameters changes, in industrial practice are applied several kinds of lubricants, starting from the hard coatings, through the sprayed lubricants, oil or water based suspensions, lubricants based on glass, artificial materials of various consistency and various kinds of liquid lubricants, especially oils.

When selecting the lubricant for experimental investigations it is necessary to take into account several factors like: various consistency of lubricants – greases, pastes, oils, as well as origins of lubricants – organic, synthetic, and mineral. Based on the previously enumerated facts, the lubricant was selected, which will be used in experimental investigations.

Summary review of all process conditions are presented in Tab. 2.

4 Experimental results
Eksperimentalni rezultati

Depending on the ratio between the punching force and the friction force on the punch, the force that acts on the bottom of the workpiece F_z can be within limits from $F_w = 0$,

***Table 2** Investigation conditions*
***Tablica 2.** Uvjeti ispitivanja*

Surface characteristics	Tool	Die (D)	*Ra*≈0,01 μm
		Punch plate (P)	*Ra*≈0,01 μm (N1), *Ra*≈0,09 μm (N3) and *Ra*≈0,4 μm (N5)
	Test-piece		*Ra*= 0,92 μm, *Rp*= 3,62 μm, *Rv*= 5,11 μm
Reduction degree: 1÷55 %			Angle of die gradient: α = 5°, 10°, 15°, 20°
Sliding path: max 70 mm			Investigation temperature: room temperature
Ironing speed: 20 mm/min			Blank holding force (F_D): 8.7; 17.4; 26.1 kN
Applied lubricants	On die side		L1, L2 and L3
	On punch side		L4
- L1 – Lithium grease with additive of the molybdenum disulfide (Li+MoS_2) - Grease - L2 – Mineral emulsifying water-soluble oil with EP, anti-wear and lubricating additives - Oil - L3 – Mineral emulsifying agency - Paste - L4 – Non-emulsifying mineral oil with mild EP qualities – Oil (ν = 45 mm^2/s)			

when $F_{frP} = F_{ir}$, to $F_w = F_{ir}$, when $F_{frP} = 0$. With that, the wall tensile stress was within limits from $\sigma_w = 0$ to $\sigma_w = F_{ir}/(2s_1b)$. If the stress σ_w exceeds the real yield stress, the destruction of the workpiece wall will occur. Due to that it is necessary that the wall tensile stress σ_w has the value as small as possible, namely the contact conditions should be selected in such a way that one obtains smaller σ_w.

The changes trends of the punching force and the friction force on the sliding path dictate the variation of the tensile stress, which can be: constant, increasing or decreasing (Fig. 7).

Tension stress is constant when selected lubricant is of a good quality. Nonsuitable lubricant that cannot sufficiently enough provide separation of contact surfaces, in most cases results in stress increase in the wall along the sliding path, while lubricants with EP additives can result in stress decrease in the wall during the ironing.

Since the expression for stress is in terms of the punching force and the friction force on the punch, which both depend to a great extent on the holding force and the die slope angle, it is logical to expect that the influence of these factors on the wall tensile stress will also be very strong [5].

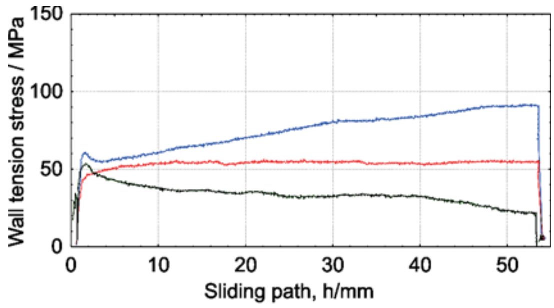


Figure 7 *Variation of the tensile stress along the sliding path*
Slika 7. *Promjena rasteznog naprezanja stijenke na putu klizanja*

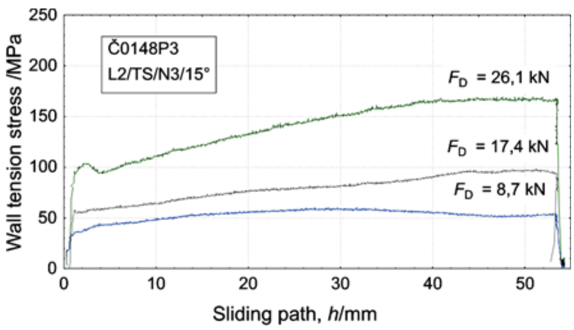


Figure 8 *Variation of the wall tensile stress with the sliding path for various holding forces*
Slika 8. *Promjena rasteznog naprezanja stijenke na putu klizanja za različite sile držanja*

In Fig. 8 is shown the dependence of the wall tensile stress on the sliding path at various holding forces. The average values of the σ_w stress, for various holding forces and all the levels of the tested factors are shown in Fig. 9. With the increase of the holding force, the increase of the tensile stress also occurs.

Variation of the σ_w stress with the sliding path for various die slope angles is shown in Fig. 10. With the increase of the die slope angle the tensile stress σ_w also increases. Dependence of the average values of the σ_w stress on the die slope angles is shown in Fig. 11. With the increase of the die slope angle the wall tensile stress increases for all the levels of the other analyzed factors.

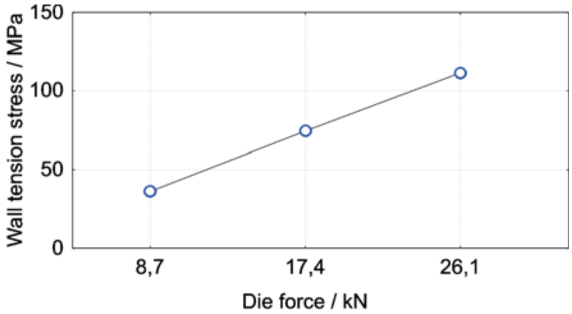


Figure 9 *Variation of the wall tensile stress with the holding force*
Slika 9. *Promjena rasteznog naprezanja stijenke o sili držanja*

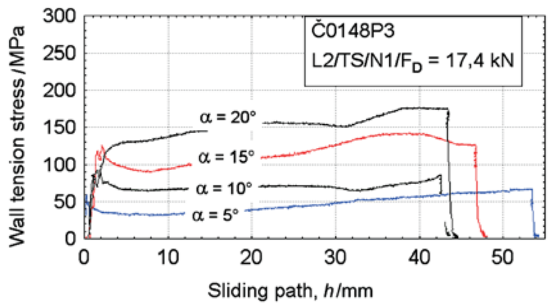


Figure 10 *Variation of the wall tensile stress with the sliding path for various die slope angles*
Slika 10. *Promjena rasteznog naprezanja stijenke o putu klizanja za različite kutove nagiba matrice*

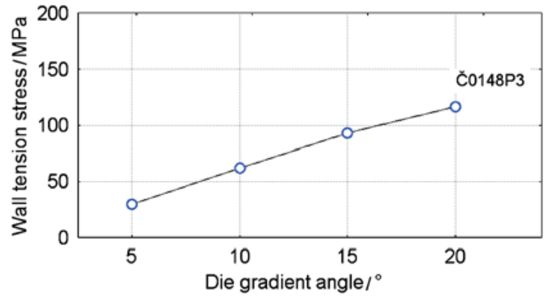


Figure 11 *Variation of the wall tensile stress with the die slope angle*
Slika 11. *Promjena rasteznog naprezanja stijenke o kutu nagiba matrice*

Dependence of the wall tensile stress on the die slope angle, at various levels of the holding force is given in Fig. 12. The maximal wall tensile stress σ_w increases with the increase of the angle α. The difference between the wall tensile stresses, which is obtained at various holding forces, increases nonlinearly with the increase of the die slope angle.

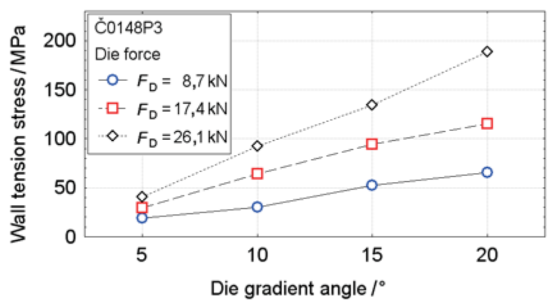


Figure 12 *Variation of the wall tensile stress with the die slope angle at various holding forces*
Slika 12. *Promjena rasteznog naprezanja stijenke o kutu nagiba matrice pri različitim silama držanja*

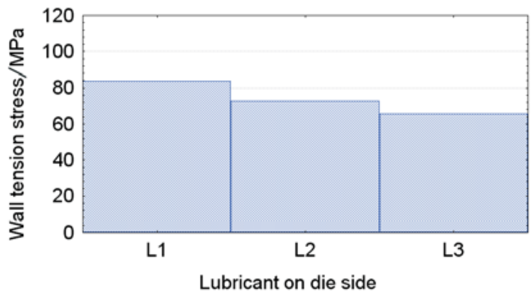


Figure 13 *Average values of the wall tensile stress for various lubricants on the die*
Slika 13. *Srednje vrijednosti rasteznog naprezanja stijenke za različita maziva na matrici*

The average values of the wall tensile stresses at application of various lubricants are shown in Fig. 13. The smallest value of stress is obtained when lubricant L3 was applied and the highest value is for lubricant L1.

The σ_w stress (average values) for various tool materials is shown in Fig. 14. The smallest value of stress is obtained when the tool with the TiN coating was applied and the highest value is for tool made of hard metal.

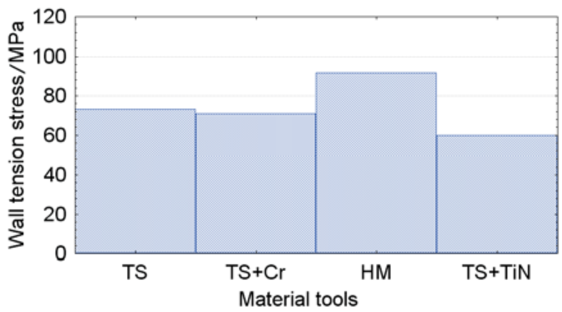


Figure 14 *Average values of the wall tensile stress for various tool materials*
Slika 14. *Srednje vrijednosti rasteznog naprezanja stijenke za različite materijale alata*

Considering that the punch roughness imposes strong influence on the value of the friction force on the punch (with the increase of roughness the force on the punch also increases), it is logical that the increase of the punch roughness will lead to the decrease of the wall tensile stress, what is shown in Fig. 15.

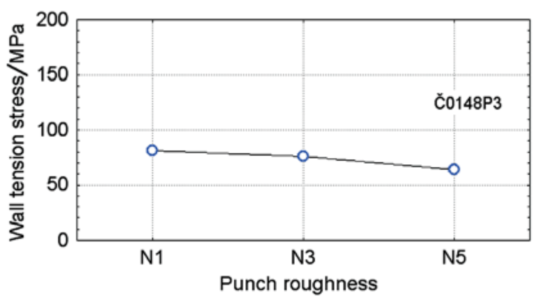


Figure 15 *Average values of the wall tensile stress for various punch roughnesses*
Slika 15. *Srednje vrijednosti rasteznog naprezanja stijenke za različite hrapavosti izvlakača*

Higher values of the friction force between the punch and the workpiece correspond to higher values of the friction coefficient on the punch side. At the same time, with the increase of the friction coefficient on the punch, the tensile force of the workpiece wall decreases. Due to significantly larger increase of the punch friction forces with respect to the decrease of the wall tensile force, the punching force increases. This statement is illustrated in Fig. 16. Similar results were obtained in paper [13] by investigating the samples made of technically pure box-shaped aluminum.

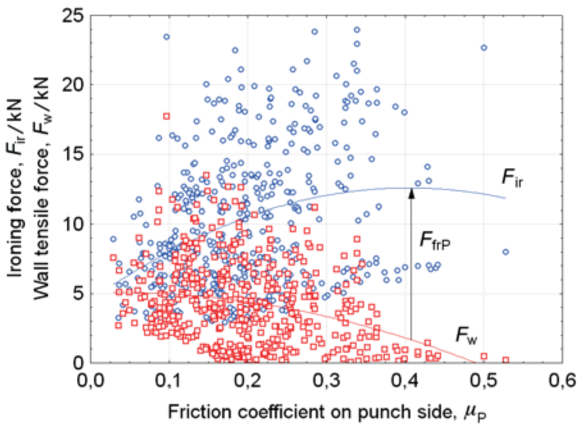


Figure 16 *Dependence of the punching force (F_{ir}) and the wall tensile force (F_w) on the friction coefficient on the punch side*
Slika 16. *Ovisnost sile izvlačenja (F_{ir}) i sile rastezanja stijenke (F_w) od faktora trenja na strani izvlakača*

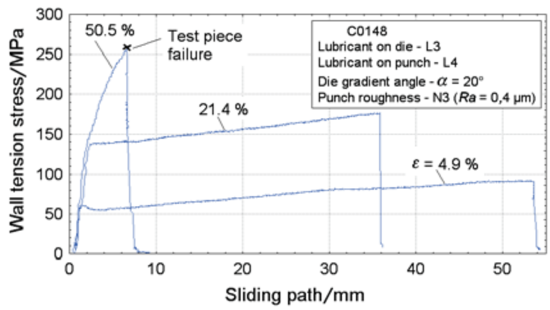


Figure 17 *Variation of the wall tensile stress at various degrees of strain*
Slika 17. *Promjena rasteznog naprezanja stijenke pri različitim stupnjevima deformacije*

The wall tensile stress on the sliding path changes depending on the way of variation of the punching force and the friction force on the punch. When these values are exceeded the destruction of the wall occurs. The characteristic example is shown in Fig. 17.

5 Numerical FE analysis
Numerička FE analiza

Numerical FE simulation enables the prediction of important output parameters of the process during deformation, such as wall tension stress, strain, temperature, ironing force course etc., in dependence on input parameters (die angle, die force, friction conditions...). In this paper, some selected experiments have been simulated numerically, with the aim to investigate physics of the process and confirm experime-ntally obtained results. Also, it is possible to estimate and illustrate interactions among influential process factors. This is important for further investigations of ironing process at broaden range of influential parameters, where developed equipment cannot be provided, such as higher velocities lead to higher temperatures of workpiece.

Finite element simulations were performed by using commercial software Simufact.forming, as a special

***Table 3** Process parameters for numerical simulations of ironing process*
***Tablica 3.** Parametri procesa za numeričku simulaciju procesa dubokog izvlačenja sa stanjenjem debljine stijenke*

Code of FE experiment	Die angle / °	Die force / kN	Thickness reduction / mm	Reduction degree / %	μ_p	μ_D
CA05Fd2V1	5	17,4	0,12	5,82	0,1436	0,0932
CA10Fd2V1	10	17,4	0,28	13,59	0,1063	0,0707
CA15Fd3V1	15	26,1	0,66	32,04	0,2562	0,0795
CA20Fd3V1	20	26,1	0,95	46,11	0,1914	0,0948

purpose process simulation solution based on MSC.Marc technology. Non-linear finite element approach was used with 3D solid elements (HEX), optimized for sheet metal forming using a "2½ D sheet mesher". It provides the most accurate results possible, for predicting thickness variations, spring-back and residual stresses.

In order to consider deformation history, numerical simulation of bending process of strip (dimension 200×20×2,01 mm) was made. The design of the dies and the punch and of the initial strip was realized using the Simufact.forming pre-processor. For calibration of bent strip bottom, additional elastic tool (spring die) was used, providing accuracy of bending angles and very small spring-back effects at the end of simulation. Fig. 18 illustrates the model of bending process in Simufact.forming pre-processor, as well as residual axial stress distribution at the end of spring-back calculation, which has been performed automatically after bending simulation.

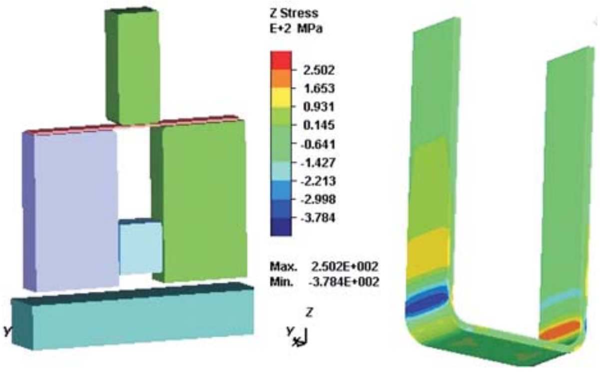


***Figure 18** Model of bending process of strip and axial stress distribution after spring-back*
***Slika 18.** Model procesa savijanja trake i raspodjela aksijalnih naprezanja poslije savijanja*

During the simulation of the subsequent ironing operation, the shape, thickness, stress, strain, and other parameters of deformation history of the previous bending operation have been automatically carried over. 3D CAD models of punch and dies with different die angles were prepared in CATIA software and imported in Simufact.forming as IGES files. Bent strip, bearing deformation history, was virtually placed on the punch model, symmetrically between dies, whereat distance between dies has defined the reduction of strip thickness, that is strain of strip.

Four "numerical experiments" were chosen and defined with the same levels of influential process parameters as in laboratory experiments, as it is shown in Tab. 3. The chosen numerical experiments are representative to illustrate influence of different die angles, reduction of strip thickness and friction conditions on values and distribution of wall tension stress during ironing process. The friction coefficients used for the contact surfaces of the punch and dies were calculated based on measured forces in experiments, and by using of equations (7) and (8), whereat the Coulomb principle being adopted. The rest parameters taken into numerical FE simulations included the same data as in experiments, listed in Tab. 1 and shown in Fig. 2.

There are a number of output results of numerical experiments of the ironing process, referring to stress, strain, strain rate, and temperature distribution in deformation zone, but only axial stress distributions, which are wall stresses, and forming load diagram are presented in this paper. Wall stress distributions in vertical cross section parallel to *x-z* plane, obtained in numerical experiments, are shown in Fig. 19. Trend of changes is the same as in laboratory experiments. It is evident that wall tension stress increases with the increase of die angle, as well as reduction of thickness.

With numerical experiments it is possible to determine and estimate wall tension stress values in any time, and any deformation zone or section, opposite to laboratory experiments, where wall tension stress was calculated as average value related to F_w, in accordance with equation (6), Wall stress distributions in the whole ironed strip are shown in Fig. 20. Z (σ_w) stress values in legend of distributions correspond to wall stress values, as it is evident in Fig. 1.

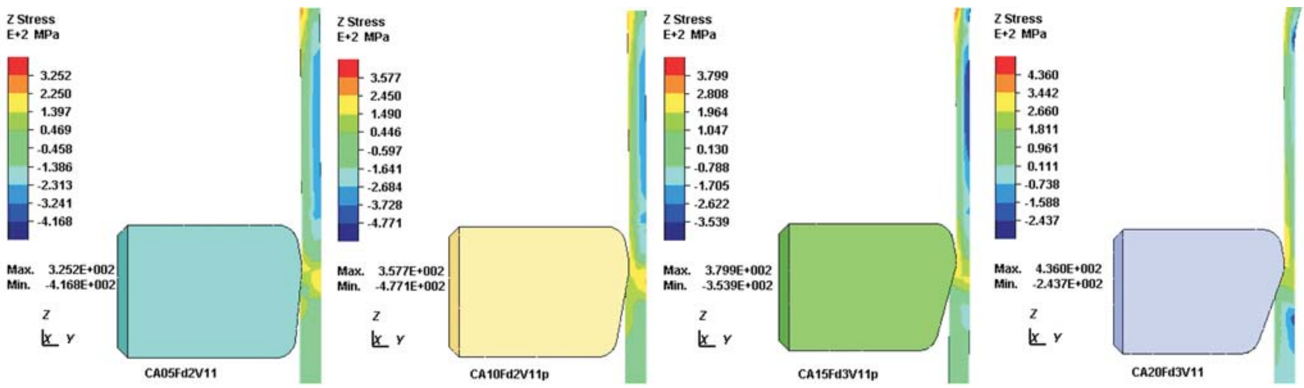


***Figure 19** Wall stress distributions in numerical FE experiments of ironing (die angle 5°, 10°, 15° and 20°)*
***Slika 19.** Raspodjela naprezanja rastezanja stijenke u numeričkom FE eksperimentu procesa dubokog izvlačenja sa stanjenjem (kut matrice 5°, 10°, 15° i 20°)*

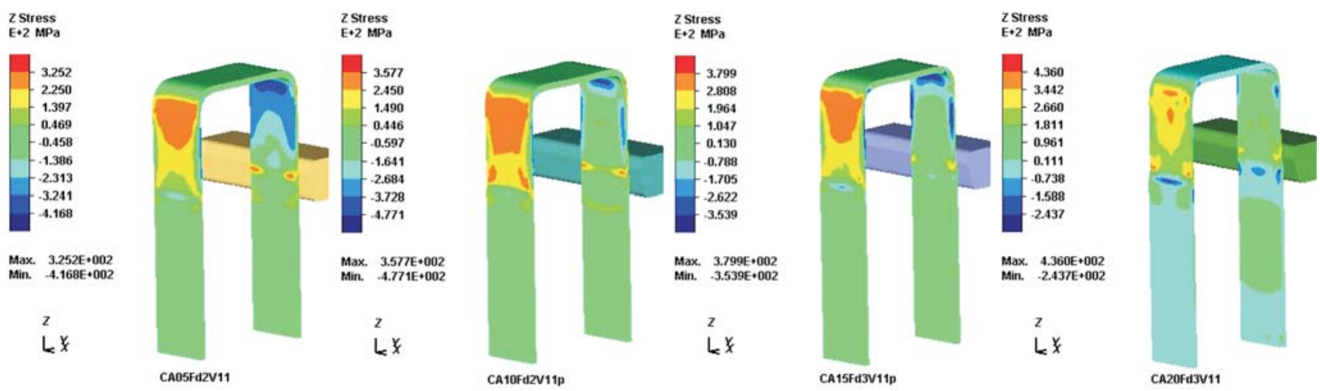


Figure 20 *Wall stress distributions at ironed strip during ironing process*
Slika 20. *Raspodjela naprezanja u stijenki trake tijekom procesa dubokog izvlačenja sa stanjenjem debljine stijenke*

It is possible to analyse the change of the wall stress along the strip thickness, outer and inner sides during ironing process. Moreover, easy variations of friction conditions on punch and dies in numerical experiment can provide useful information about wall stress distribution in deformation zone. It could be a powerful tool for the ironing process optimization.

It is already emphasized that the tensile stress diagrams as functions of the die slope angle and the holding force, namely the realized deformation at ironing in Fig. 9 and Fig. 10 were obtained based on the measured forces and application of the analytical expressions in equations (4), (5) and (6), which means that the obtained values of the tensile stresses are averaged. In numerical simulations estimated values and presented distributions of the tensile stress along the strip, and in all the cross-sections, during the process, point to the fact that the tensile stresses have their maximum in the zones of the ironed workpiece outside of the deformation zone, further away from the die exit angle (e.g., from 49 MPa to 145 MPa, for the die angle of 5 °, or from 148 MPa to 260 MPa for the die angle of 20 °).

Correspondent diagram with minimum and maximum values of wall stress on the outer surface of strip is shown in Fig. 21. This of course must be taken into consideration in estimates of the ironing process successfulness. At the same time, this is how the situations are explained of the strip tearing at larger realized strains, when the tensile stresses on the external strip surface exceed the allowable value for the corresponding sheet material, what occurred in some experiment.

It is known that the measurable indicator of the verification of the experimental-numerical results in modelling and simulation of various forming processes is

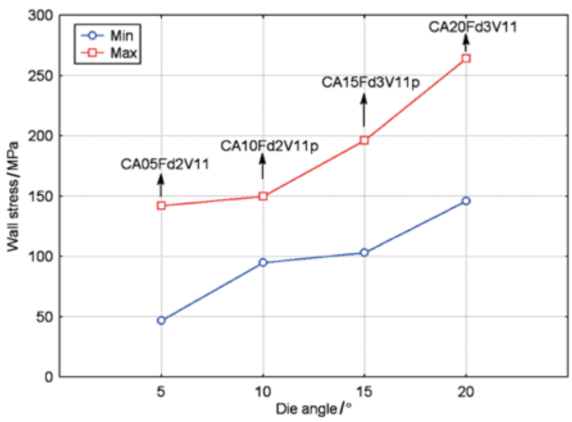


Figure 21 *Wall stress – die angle diagram, numerical predictions*
Slika 21. *Dijagram naprezanja stijenke – kut nagiba matrice, numerička procjena*

the diagram of the forming force, since it includes all the considered process influential factors. For that purpose the comparative diagrams of the forming force were prepared, obtained experimentally, by measuring on the machine and their FE estimates in numerical experiments. In Fig. 22 are shown the comparative diagrams for all the four numerical experiments. As can be seen, the predictions are in good agreement with experimentally obtained forces.

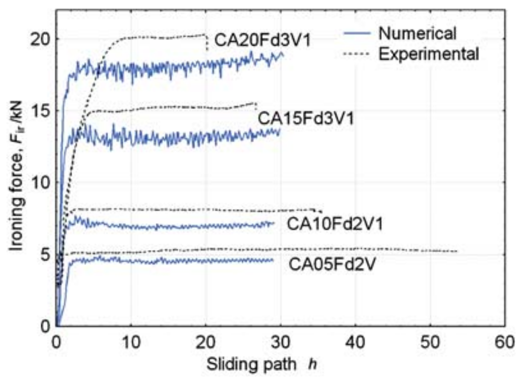


Figure 22 *Forming force diagram*
Slika 22. *Dijagram sile izvlačenja*

6 Conclusions
Zaključci

Results showed that techniques of physical process modelling at laboratory device and numerical FE simulations can be efficiently used for comprehensive analysis of the ironing process. Considering limitations and advantages of both methods, their integrated application has complementary advantages and enables determination of the process parameters' influences (die angle, die force, friction conditions on punch and dies, velocity) on output performances of the formed workpiece. From this investigation the following conclusions can be summarized:

a) Physical experiments are necessary for defining accurate input data for overall FE numerical analysis, so, the combined experimental-numerical approach is recommendable as the best approach for the ironing research and similar forming processes. Friction coefficient values that describe the state between contacts are determined by measurement of forces on die and punch, as well as total process force on machine. Considering the fact that friction coefficient value changes during the ironing process, mean values of friction coefficient of contact pairs are taken for each numerical experiment, shown in detail in Tab. 3. Even though it is one of the disadvantages of numerical FE simulations to use constant value of the friction coefficient, which means that there are no changes in conditions of contact friction, the results of both applied methods have good agreement.

b) By numerical simulations it is possible to know the distribution of wall stress in each cross section and the entire sliding path, as well as to determine deformation forces of ironing process. The value of the wall tension stress, obtained by physical experiment, represenst the mean value of the wall tension stress during sliding, calculated by equation (5), because it is not possible to determine distribution of wall stress in cross section by physical modelling. In Fig. 9 to Fig.12 are shown the dependences of the wall tensile stress at various process parameters. Unlike this, with numerical simulation it is possible to determine the spatial distribution of stresses at any moment.

c) The trends of the punching force and the friction force on the punch variations along the sliding path dictate the variation of the tensile stress, which can be: constant, increasing or decreasing (see Fig. 7). In experiments whose results are shown in this paper, the force trend is kept constant within physical modelling as well as in numerical simulations. Numerical estimation of forming loads is somewhat lower than of those recorded by the machine, but the difference is up to 10 %, as it is shown in Fig. 22. Numerical models do not follow the real worsening of contact friction conditions that exists in physical modelling, due to the fact that constant values of friction coefficient are taken for applied Coulomb law.

d) By increasing the friction coefficient on the punch one can decrease the wall tensile stress, but simultaneously the punching force will increase. On the other hand, the variation of the punching force does not unambiguously testify about the corresponding changes of the tensile stresses in the workpiece critical cross-section. At small punching forces one regularly obtains small wall tensile stresses, while at high punching forces, depending on the realized contact conditions, it is possible to obtain both large values of the wall tensile stresses as well as the small values.

e) With increase of the die angle and increase of reduction rate of the wall thickness during the ironing, wall tensile stress value increases (Figs. 10 and 11 for experiments, and Figs. 19 and 20 for numerical results). For large wall thickness reduction, tensile stress values exceed the value of the material tensile strength resulting in tearing of the sheet strip material (Fig. 17). This is confirmed by experiment and numerical simulation.

f) Absolute values of presented results in this paper cannot be directtly comparable with those obtained in other similar references, since a large number of factors (tribological, materials, shapes, tools, modelling devices and so on) affect the values of the process outputs (forces, stresses, strains). The trends of the results obtained in this study are consistent with the trends obtained in the references.

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