EXPERIMENTAL AND NUMERICAL DETERMINATION OF THE TENSILE STRESSES IN THE WALL DURING STEEL SHEET IRONING

D. Adamović[1], V. Mandić[1], M. Stefanović[1], S. Aleksandrović[1], M. Živković[1], Z. Golušija[2], S. Ranđelović[1]

1. *Faculty of Mechanical Engineering, University of Kragujevac, Serbia*
2. *Institute for Technology of Nuclear and Other Raw Materials (ITNMS), Belgrade, Serbia*

ABSTRACT
This paper is dealing with analysis of the ironing process, by application of the experimental modeling and numerical FE simulations. Since the two approaches are complementary, abundance of obtained results enables overall analysis of the process with taking into account numerous influential factors and their interactions on the output process performances ad the quality of the machined piece.
Experimentally obtained results were confirmed by numerical FE analysis, which were realized at the same levels of the influential factors, for the purpose of verification and additional explaining of the process nature, as well as understanding the influence of various parameters on the machined piece wall tensile stress in the selected experiments.
KEYWORDS: Ironing, Wall stress, Tribology conditions, Tribo-modeling, FE numerical simulation

1. INTRODUCTION

Friction forces that act on the external and internal part of the element have different directions during ironing. The friction forces senses are opposite because the piece is moving through the die during drawing, and thus the friction force at the external surface has the sense opposite of the drawing. At the same time, at the expense of ironing, the piece is being extended, thus the friction force at the internal surface of the piece will be directed in the sense of drawing (Figure 1). Force F_w, which acts on the bottom of the piece, causes the appearance of the tensile stresses in the machined piece wall, both in the drawn portion and in the deformation zone. Those tensile stresses have the maximal value at the exit of the machined piece from the die and they are decreasing to certain minimal value, which they have at the entrance of the machined piece in the deformation zone /1/.

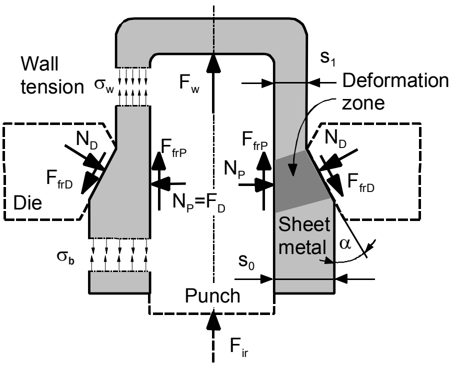

Figure 1: Scheme of the forces action on the thin sheet.

The wall tensile stress in the drawn portion of the working piece, besides other, depends on the tribological conditions on the contact surfaces between the punch and die, at one side and the machined piece at the other 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 vale of the tensile stress σ_w.

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.

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 tribo-models. The investigation of tribological conditions takes much more time and is considerably more expensive. Investigations on tribo-models are more often practiced. Modeling 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 process.

It is possible to find in literature the whole series of tribo-models which were mainly developed for particular purposes /2,3,4,5/. 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. From 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 tribo-model of 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.) /6/.

The wall ironing process has been studied using combined experimental and numerical approach in many researches, which results are available in literature /7,8/. Usage of program for numerical simulation and physical modeling techniques are complementary, due to their advantages and restrictions. The application of these methods represents the new concept in designing of processes and tools /9,10/. 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. EXPERIMENTAL INVESTIGATION

Experimental investigations in this paper were conducted on the original tribo-model of ironing, which double sided simulates the contact zone with the punch and die /6/. This model enables realization of the high contact stresses 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 tribo-model is shown in Figure 2a, while the device appearance is shown in Figure 2b.

The bent strip of thin sheet 7, in the U shape, (sample) is being placed on the "punch". The stripe is being act upon by "matrices" 2 with force F_D. 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. The sample is passing (sliding) between dies, by the action of the force F_{ir} on the punch front, when the sample wall is being thinned (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.

Plates 6 and dies 2 can be made of various materials, as well as with various roughnesses, while dies can have various slope angle α.

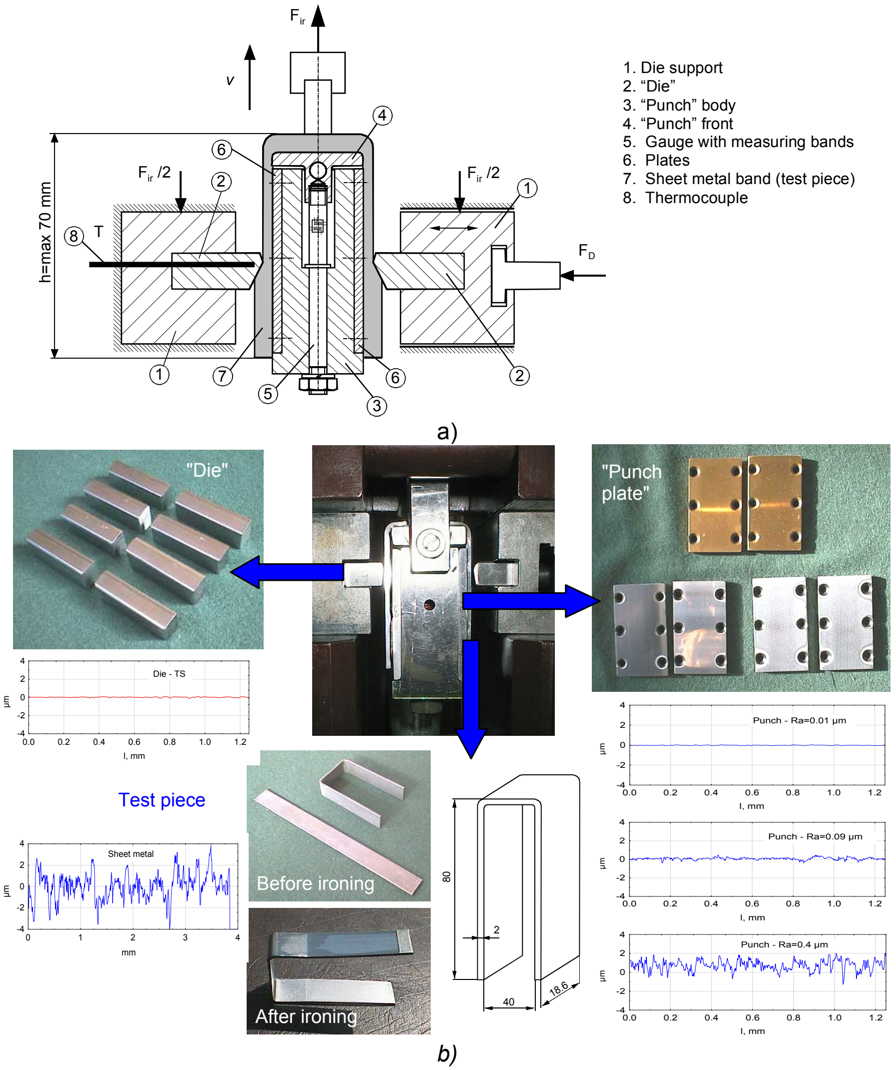

Figure 2: Scheme (a) and appearance of the model (b) used in this investigation.

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

The total drawing force F_{ir} represents the sum of the friction force between the punch and the machined piece, F_{frP} and the force that acts on the bottom of the strip, F_w, (Figure 1):

$$F_{ir} = F_{frP} + F_w \tag{1}$$

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 (1) follows that:

$$F_w = F_{ir} - F_{frP} \ , \tag{2}$$

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:

$$\sigma_w = \frac{F_w}{2 \cdot b \cdot s_1} \ , \tag{3}$$

where: b is the sample thickness,

s_1 is the strip thickness after ironing.

Friction coefficients on punch (μ_P) and die (μ_D) sides can be calculated by equations (4) and (5):

$$\mu_P = \frac{F_{frP}}{2 \cdot F_D} \tag{4}$$

$$\mu_D = \frac{F_{ir} \cdot \cos\alpha - 2 \cdot F_D \cdot \sin\alpha}{F_{ir} \cdot \sin\alpha + F_D \cdot \cos\alpha} \tag{5}$$

For experimental investigations in this paper was chosen the low carbon steel thin sheet, tempered by aluminum, mark Č0148P3 (WN: 1.0336; DIN: DC 04 G1/Ust 4, Ust 14). It belongs into a group of high quality thin 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 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. The die surface was polished (R_a≈0.01 μm), while the punch surfaces were produced with three different qualities: R_a≈0.01 μm, R_a≈0.09 μm and R_a≈0.4 μm. The rough punch surface (R_a≈0.4 μm) was chosen in order to obtain the value of the friction coefficient on the punch side as high as possible.

Appearance of the strips, on which the investigations were performed, is shown in Figure 2b. Mechanical properties, surface characteristics, as well as other data, are given in Table 1 and in Figure 2b.

Considering that the plastic deforming process 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. Their review is presented in Table 1.

Table 1: Properties of investigated material and investigation conditions.

<table>
<tr><td colspan="2"></td><td>Material</td><td>Mechanical properties</td><td>Surface characteristics</td></tr>
<tr><td rowspan="2">Tool</td><td>Die (D)</td><td>▪ TS*
▪ TS + Cr plate
▪ TS + TiN plate
▪ HM**</td><td rowspan="2">TS Hardness
60÷63HRC

HM Hardness
1200HV30</td><td>R_a≈0.01 μm (N1)</td></tr>
<tr><td>Punch plate (P)</td><td>▪ TS*
▪ TS + Cr plate
▪ TS – TiN plate
* - TS – Tool steel, Č4750 (DIN17006: X165CrMoV12)</td><td>R_a≈ 0.01 μm (N1),
R_a≈ 0.01 μm (N3) and
R_a≈ 0.4 μm (N5)</td></tr>
<tr><td colspan="2">Test-piece</td><td>Č0148P3 (WN: 1.0336; DIN: DC 04 G1/Ust 4)
Thickness: 2.0 mm
width: 18.6 mm</td><td>R_p = 186 MPa
R_m = 283 MPa
A_{80} = 37.3 %
n = 0.2066
r = 1.09009</td><td>R_a = 0.92 μm
R_p = 3.62 μm
R_v = 5.11 μm</td></tr>
<tr><td colspan="3">Reduction degree: 1÷55%</td><td colspan="2">Angle of die gradient: α = 5°, 10°, 15°, 20°</td></tr>
<tr><td colspan="3">Sliding path: max 70 mm</td><td colspan="2">Investigation temperature: room temperature</td></tr>
<tr><td colspan="3">Ironing speed: 20 mm/min</td><td colspan="2">Blank holding force (F_D): 8.7; 17.4; 26.1 kN</td></tr>
<tr><td colspan="2" rowspan="2">Applied lubricants</td><td>On die side</td><td colspan="2">L1, L2 and L3</td></tr>
<tr><td>On punch side</td><td colspan="2">L4</td></tr>
<tr><td colspan="5">* - TS – Tool steel, Č4750 (DIN17006: X165CrMoV12)
** - HM – Hard metal, WG30 (DIN4990: G30)
- 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 (v = 45 mm²/s)</td></tr>
</table>

The 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 Table 1. Tests have been performed under laboratory conditions (v = 20 mm/min, T=20°C).

Experimentally obtained data for true stress - true strain relationship, that is flow curve, was fitted in exponential form. Equation (6) was finally used for further numerical description of material flow and behavior during FE ironing simulation, where K is true stress and φ is true strain.

$$K = 491.6874 \cdot \varphi^{0.2186} \qquad (6)$$

3. EXPERIMENTAL RESULTS

Depending on the ratio between the punching force and the friction force on the punch, the force that acts on the bottom of the machined piece F_z can be within limits from $F_w = 0$, 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 machined piece 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 are dictating the variation of the tensile stress, which can be: constant, increasing or decreasing.

Since the expression for stress is in terms of the punching force and the friction force on the punch, which both depend, to the 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 /8/.

In Figure 3 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 f the tested factors are shown in Figure 4. With 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 Figure 5. With increase of the die slope angle the tensile stress σ_w also increases. Dependence of the average values of the σ_w stress with the die slope angles is shown in Figure 6. With increase of the die slope angle the wall tensile stress increases for all the levels of other analyzed factors.

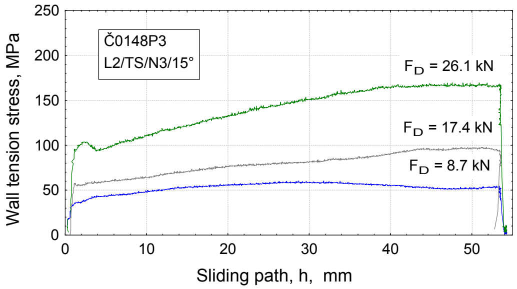

Figure 3: Variation of the wall tensile stress with the sliding path for various holding forces.

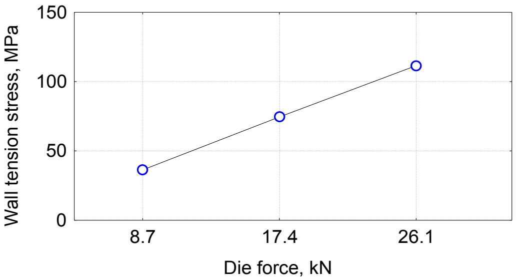

Figure 4: Variation of the wall tensile stress with the holding force.

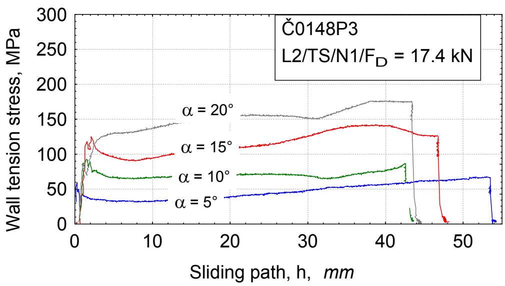

Figure 5: Variation of the wall tensile stress with the sliding path for various die slope angles.

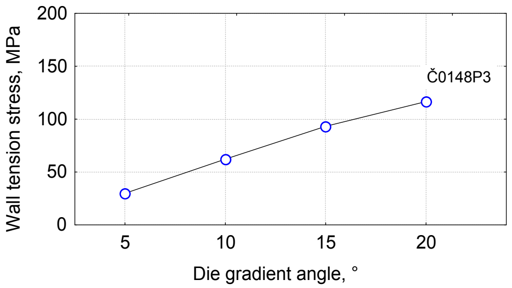

Figure 6: Variation of the wall tensile stress with the die slope angle.

The average values of the wall tensile stresses at application of various lubricants are shown in Figure 7. 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 Figure 8. 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.

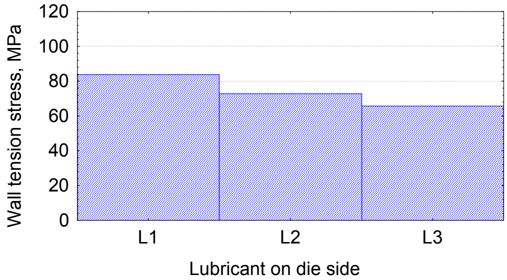

Figure 7: Average values of the wall tensile stress for various lubricants on the die.

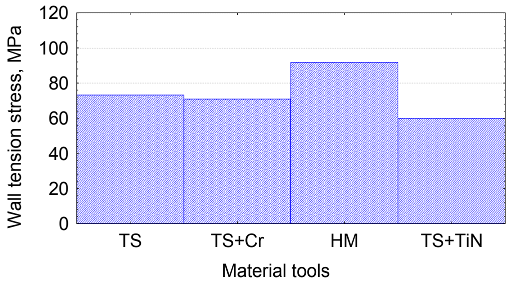

Figure 8: Average values of the wall tensile stress for various tool materials.

Considering that the punch roughness imposes strong influence on the value of the friction force on the punch (with increase of roughness the force on the punch also increases), it is logical that increase of the punch roughness will lead to decrease of the wall tensile stress, what is shown in Figure 9.

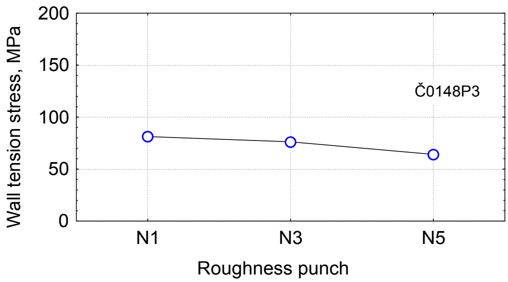

Figure 9: Average values of the wall tensile stress for various punch roughnesses.

4. FE ANALYSIS OF IRONING PROCESS

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. It is important for further investigations of ironing process at broaden range of influential parameters, where developed equipment is not able to provide, such as higher velocities lead to higher temperatures of workpiece.

Finite element simulations were performed by using commercial software Simufact.forming, as a special 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 200×20×2,06mm) 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.

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, where at distance between dies have 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 Table 2. 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 (4) and (5), whereat the Coulomb principle being adopted. The rest parameters taken into numerical FE simulations included the same data as in experiments, listed in Table 1 and shown in Figure 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 stress, and forming load diagram are presented in this paper.

Wall stress distributions in numerical experiments are shown in Figure 10. Trend of changes are 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, in opposite of laboratory experiments, where wall tension stress was calculated as average value related to Fw, in accordance with equation (3), Axial stress distributions in the whole strip and in vertical cross section parallel to x-z plane

Table 2: Process parameters for numerical simulations of ironing process.

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

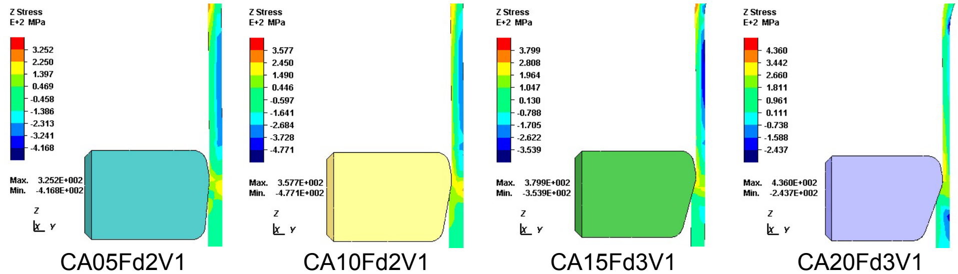

Figure 10: Wall stress distributions in numerical FE experiments of ironing.

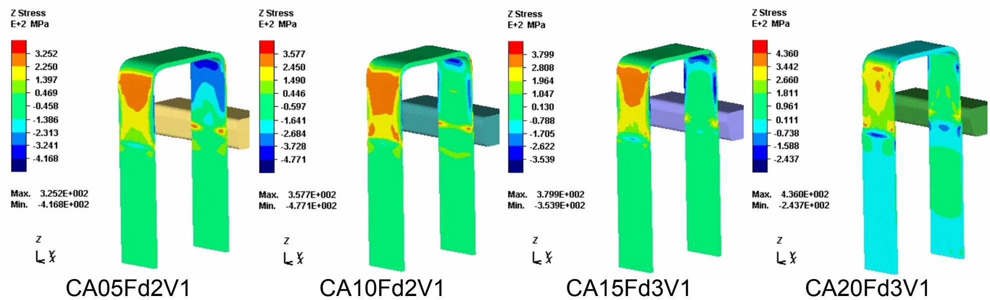

Figure 11: Axial stress distributions at ironed strip during ironing process

are shown in Figure 11. It is possible to analyse change of the wall stress along 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 powerful tool for the ironing process optimization.

5. CONCLUSIONS

This paper presents results of a integrated experimental and numerical approach were presented, in order to investigate the important process parameters of the ironing process under different process conditions. For successful ironing process, it is necessary that the wall tension stress has the smallest possible value, which means that the contact conditions should be selected in such a way that the smallest possible σ_w is obtained. Trends of changes of ironing force and friction force on the punch on sliding path influence the change of tension stress, which can be: constant, increasing or decreasing.

Calculated values of the wall tension stress, obtained by physical experiments, represent the mean value of the wall tension stress during ironing, because is not possible to determine distribution of tension stress in cross section. Unlike the laboratory experiments, with the numerical modelling, it is possible to determine the spatial distribution of stresses at any moment. However, the disadvantage of numerical experiment is that, in one calculation the constant value of friction coefficient is used, so the conditions within the contact are unchanged. In the real process, the contact conditions in ironing are changed, which causes the change of the drawing force, which consequently lead to alternation of wall tension stress.

Strip ironing modelling experiments are necessary for defining accurate input data for overall FE numerical analysis, thus the integrated experimental-numerical approach is recommendable as the best approach for the ironing research and similar forming processes. By combining the physical with numerical approach it is possible to determine the distribution of residual stress in each cross section and the entire sliding path, as well as to determine forming loads of ironing process.

It can be concluded that the integrated experimental-numerical approach of investigation has the capability to determine the influence of various process parameters in ironing, such as die angle, die force, friction conditions on punch and dies, velocity, on process course, outputs and forming load.

6. REFERENCES

1. *Avitzur, B.*: Handbook of Metal-Forming processes, JOHN WILEY & SONS Inc., New York, (1983).
2. Andreasen J.L., Bay N.: A strip reduction test for measurement of lubricate in ironing, 19th IDDRG Biennial Congress, Eger, 1996., 435-444.
3. Kawai N., Nakamura T., Dohda K.: Development of anti-weld ability test in metal forming by means of strip-ironing type friction testing machine, Trans. ASME, J. Eng. Ind., Vol. 104, (1982) 375-382.
4. Lange K., Grabener T.: Tribologie in der Umformtechnik-Reibung, Schmierung, Schmierstoffprufung, 3th Intern. Colloq., Esslingen, 1982., 15.1-15.14.
5. Deneuville P., Lecot R.: The study of friction in ironing process by physical and numerical modeling, Journal of Materials Processing Technology, 45, (1994), 625-630.
6. Adamovic D.: Conduct of materials in contact at processes of plastic forming with high working pressures, Doctoral thesis, The Faculty of Mechanical Engineering, Kragujevac, 2002., (in Serbian).
7. H.C.E. van der Aa, M.A.H. van der Aa, P.J.G. Schreurs, F.P.T. Baaijens, W.J. van Veenen, An experimental and numerical study of the wall ironing process of polymer coated sheet metal, Mechanics of Materials 32 (2000), 423-443.
8. Schunemann M., Ahmetoglu A.M., Altan T.: Prediction of process conditions in drawing and ironing of cans, Journal of materials Processing Technology 59(1996), 1-9.
9. Mandic V.: Physical modelling and numerical simulation as basis of new concept for tool design for hot metal forming, PhD thesis, Faculty of Mechanical Engineering, Kragujevac, 2002., (in Serbian).
10. Mandić, V., Adamović, D., Jurković, Z., Stefanović, M., Živković, M., Ranđelović, S., Marinković, T.: CAE Analysis of Ironing Process with Experimental Verification, MOTSP 2010 International Scientific Conference Management of Technology – Step to Sustainable Production, 2-4 June 2010, Rovinj.