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ANALYSIS OF THE TEMPERATURE CHANGE ON THE TOOL AND WORK PIECE DURING THE IRONING PROCESS

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Summary: *The purpose of the paper is to investigate the temperature field in the contact between the tool and workpiece in the ironing process of strip, by application of integrated physical modeling and numerical simulation approach. The physical modeling of the ironing process was performed on originally developed strip ironing device, with installed the thermocouples at the position close to the contact surface of the die. Because the laboratory equipment allowed experiments only at lower deformation rates, there was a need for numerical estimations of the temperature fields at higher speeds. Moreover, there were experimental limits in measuring the contact pressures and temperature at high speeds which were eliminated by application of the FE simulations. For this purpose a series of the numerical experiments was conducted. The presented results show good agreement of experimental and numerical results, in the range of low velocities, with tendencies of the temperature increase with increase of speeds. The concluding remarks provide recommendations for successful forming.*

Keywords: *ironing, temperature, physical modeling, numerical simulation, finite element method*

1. INTRODUCTION

During the ironing process an increase of temperature occurs due to material deformation as well as due to the friction at the tool and workpiece interface.

Due to the plastic deformation of material and friction between the ironed material and tool, an increase of temperature occurs, especially at higher deformation speeds. Increased temperature within the interface can significantly influence changes of the lubricant's characteristics, through the change of the lubricant's viscosity. Also, the increased temperature can intensify the tool wear process. In ironing the tin coated thin sheets temperature significantly influence state of the tin coating. From the aforementioned reasons, it is necessary to take into account the generated heat at the

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interface, especially at the higher deformation speeds, and enable its conducting away from the contact by the lubricant, which at the same time plays the coolant's role [1]. Research that is dealing with these problems is mainly related to high-speed ironing processes.

Generated heat is being conducted partially to the tool, out of that the larger portion is being conducted to the die and the smaller portion to the punch. Due to the higher strain and higher sliding speeds between the workpiece and the die, the heat generated in that contact is much larger than the heat in the contact with the punch [2].

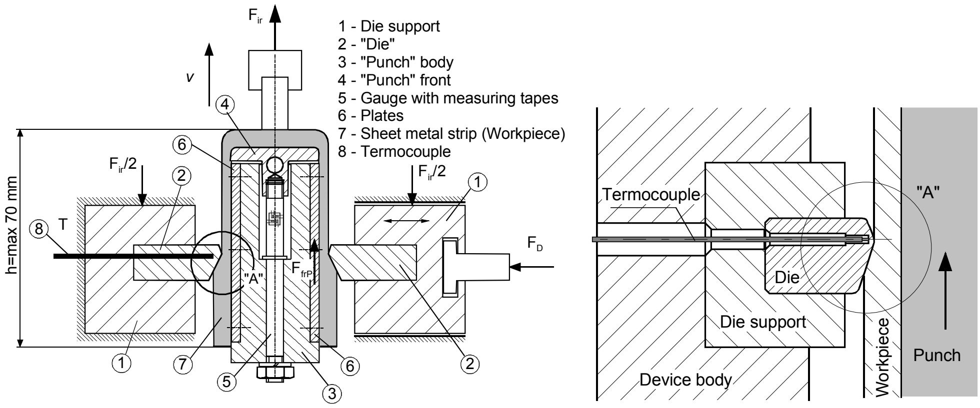
For the food and beverage cans steels thin steel sheets with the tin coating (white thin sheets). The melting temperature of tin is 323°C and it is very important that this temperature is not exceeded during the processing. In the opposite case, if this temperature is exceeded, the larger roughness of the surface would appear what would disrupt the forming process. Also, temperature increase can lead to the failure of the tin coating layer continuity and such a can would be useless [3].

Regardless of the fact that ironing is a cold forming processes, temperatures that arise can be significant. The conducted measurements at the third ring in the manufacturing conditions show that temperatures of 150 to 200°C are being reached at the press velocities at which 60 to 260 cans are being produced per minute (punch speed up to 12 m/s) [4]. By using even faster presses (400 pieces/min – 16 m/s), which is now the trend in manufacturing; the risk exists that the temperature of 232°C could be exceeded. This level of temperatures being realized with intensive lubrication by emulsions, where the lubricant also serves for removal of the generated heat. If that haven't been so, temperatures in the contact areas would be significantly higher, even at significantly lower speeds.

Often it is not possible to experimentally measure temperatures and working pressures directly at the interface. Therefore many researchers apply the thermo-mechanically coupled finite element simulations for estimates of the temperature and pressure distributions in the contact between the tool and the workpiece in ironing. Kim et al. [5] performed a series of FE numerical simulations of the tribo tests during ironing to establish influence of lubricant on the temperature and pressure distributions in the contact. The main aim of the coupled thermo mechanical analyses in this work is to gain understanding of heat development and its conduction in the contact for the high speeds that were not possible to be investigated by the experiments.

2. EXPERIMENTAL SETUP

Investigations were performed on the original model of ironing, which simulates double-sided the contact zone between the die and the punch [6]. 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 and others). The schematics of this model is presented in Fig. 1a, while in Fig. 1b is shown placing of the thermocouple for temperature measurements.



a) b)

Fig. 1 *Strip ironing device: schematics (a) and placing of the thermocouple for temperature measurements (b)*

Strip ironing device was installed on the special machine for testing thin sheets ERICHSEN 142/2.

For experimental investigations in this work the low carbon steel thin sheet was selected. It was aluminum tempered, marked EN: DC04 (WN: 1.0336). The material belongs to a group of the high quality thin sheets aimed for the metal forming process and it has properties required by standard SRPS EN 10130:2004.

For the die and punch material the alloyed tool steel (TS) EN: X160CrMoV121 (WN: 1.2601; DIN17006: X165CrMoV12) was selected. The die and the punch surfaces were polished (Ra≈0.01 μm).

All the tests were conducted at the room temperature, with ironing speeds of 20 and 250 mm/min and the punch stroke of maximum 70 mm. Strain ranged between 3.5 to 24% and it was realized by various holder force F_D.

3. NUMERICAL MODEL

To estimate the heat dissipation during the ironing process due to the heat generation by plastic work and friction and its transfer from the workpiece to the die as well as the heat loss to the environment, a series of numerical FE simulations were carried out using commercial software Simufact.forming. The coupled thermal-mechanical approach was applied. The finite element solver was enhanced version of MARC solver developed on the basis of displacement method.

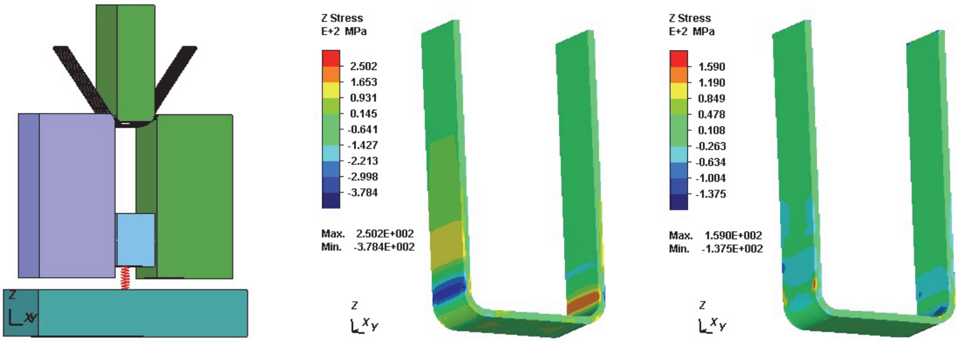
The environment of the process is also important in considering the heat transfer between workpiece and tool and radiation to the environment. Heat properties of the workpiece and tools were also defined, including the initial temperatures, heat transfer coefficients and emissivity coefficients to the surrounding area.

Non-linear finite element approach was used with 3D solid elements (HEX), optimized for sheet metal forming using a "2½ D sheet mesher".

In order to consider the deformation history the 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.

Initial mesh was generated automatically using Sheetmesh mesher and Hexahedral elements (element size 1mm, number of FE 7268) in two layers of thickness (Fig. 2). All tools were considered as rigid. For calibration of bent strip bottom, additional elastic tool (spring die – rigid tool lying on spring) was used, providing accuracy of bending angles and very small spring-back effects at the end of simulation. Figure 2 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.

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 CAD software and imported into Simufact.forming as IGES files [7]. Bent strip, bearing deformation history, was virtually placed on the punch model, symmetrically between dies, where distance between the dies defined the reduction of strip thickness, i.e. strain of the strip. Sheetmesh mesher was used for remeshing bent strip in three layers per thickness. Total number of hexahedral elements was 10908 in the beginning of simulation (see fig. 6a). In order to avoid problems in simulation due to large distortion of initial mesh in deformation zone during the ironing, remeshing criteria and parameters were defined (strain 0.4, element size 1mm and two refinement boxes in contact zones close to dies).



a) b) c)

Fig. 2 *Numerical model of bending process, tools and strip during bending simulation (a) axial stress distribution in bended strip, prior (b) and after spring-back (c)*

Heat transfer from workpiece to dies were modeled using rigid dies with heat conduction effects. For that purpose Overlay hex mesher was used for die meshing, with refinement box covering die angle zone. Total number of hexahedral elements of die was 6396. Die and workpiece mesh and position of strip and tools in numerical model of ironing process were shown in Fig. 2.

In coupled thermal-mechanical numerical simulations the critical input parameters are heat properties of workpiece and tools, initial temperatures, heat transfer and emissivity parameters as well as friction properties for the interface. As numerical experiments relay on experimental data summary of additional input data.

"Numerical experiments" were chosen, with the same levels of influential process parameters as in laboratory experiments, with exception of the ironing speed.

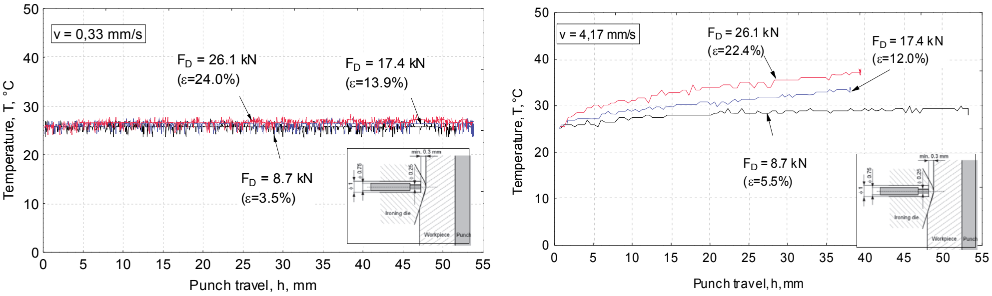
In fact, two of them have the same speeds (0.33 and 4.17 mm/s), but four numerical experiment were carried out with higher speeds, in order to illustrate its influence on distribution of temperature in workpiece and dies.

4. EXPERIMENTAL AND NUMERICAL RESULTS

When planning experiments for which the results are presented in this work, it was expected that the temperature increase would not be significant. This was later confirmed in experiments, considering that it was not possible to realize high deformation speeds ($v_{\max}$=250 mm/min) on the available laboratory press.

Temperature was measured along the whole sliding path for each sample. Dependence of the temperature variation on the sliding path for various deformation speeds and different holder forces (different strains) is shown in Fig. 3. Diagrams were obtained at deformation speeds (punch step velocity) of 20 and 250 mm/min (0.33 and 4.17 mm/s, respectively).

At deformation speed of 0.33 mm/s temperature increase along the corresponding sliding path (Fig. 3a) was very small and it ranged within the limits of measurements error (± 1.5°C). With deformation speed increase the increase of temperature occurs as well. Also, with increase of the degree of deformation at deformation speed of 4.17 mm/s somewhat higher increase of temperature was noticed (Fig. 3b). This temperature increase with respect to environment temperature (room temperature) was 4 to 12°C where the lower temperatures correspond to the lower strain. It was considered that the initial temperature, namely the environment temperature is exactly the temperature measured at the beginning of the experiment, was shown on diagram when the punch stroke is equal to zero. It should be emphasized that it was always taken care that enough time elapses between tests with different samples so that the punch temperature can be equalized with the temperature of the environment.



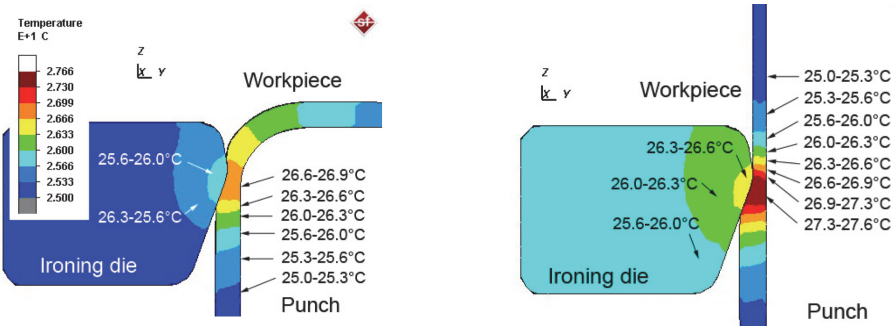
a) b)

Fig. 3 *Temperature variation with punch step at different holder forces (deformation degrees), for deformation speeds of: a) 0.33 mm/s; b) 4.17 mm/s.*

While it was possible in laboratory conditions to monitor the temperature variation only within the die at the point close to the contact surface, numerical models of the ironing process enable monitoring the thermal effects of the process at any arbitrary moment and at any speed within the workpiece and the tool. The temperature distribution in the process derived by numerical model at deformation speed of v=0.33

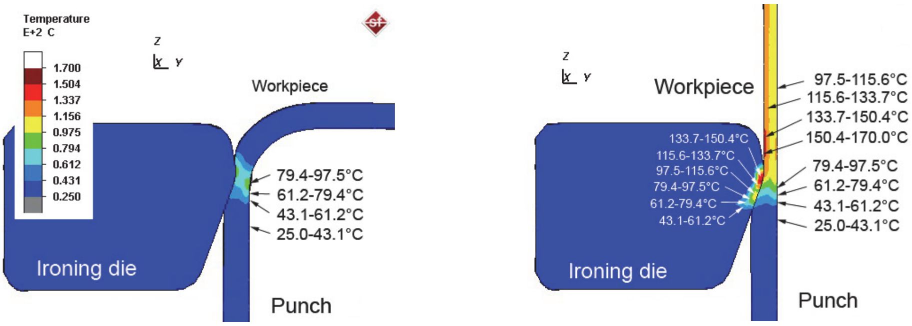
mm/s in different phases of the process (punch step *h*=3 mm and 35 mm) is presented in Fig. 4. In the deformation zone of the workpiece in the immediate contact with the tool, an increase of temperature occurs due to plastic deformation and the contact friction. The portion of the generated heat is being conducted to the die. Due to the small deformation speed and consequently longer contact time between material and the tool, the heat is conducted and distributed to the whole die. Simultaneously the workpiece which is leaving the contact is being cooled down due to the radiation effects of the heat to the environment. From the initial 25°C, the temperature within the workpiece reaches maximum value of 27.6°C while in the die at position 0.3 mm from the contact surface, same as in the experimental measurements, temperature reaches value of 26.6°C.

At significantly higher deformation speeds (*v*=10000 mm/s) which correspond to industrial conditions in manufacturing 250 cans per minute the temperature distribution is quite different as it is shown in Fig. 5. As opposite to the previous numerical experiment, already at punch stroke of 3 mm, after the first contact with the die, temperature in the workpiece reaches value of 97.5°C due to high sliding speeds in the contact and influence of friction. At the end maximum reached temperatures were 166°C in the workpiece were and 133°C in the die were at the position of the thermocouple.



h=3 mm h=35 mm

Fig. 4 *Temperature variation in the die and the workpiece at ironing speed of v=0.33 mm/s*



h=3 mm h=35 mm

Fig. 5 *Temperature variation in the die and the workpiece at ironing speed of v=10000 mm/s*

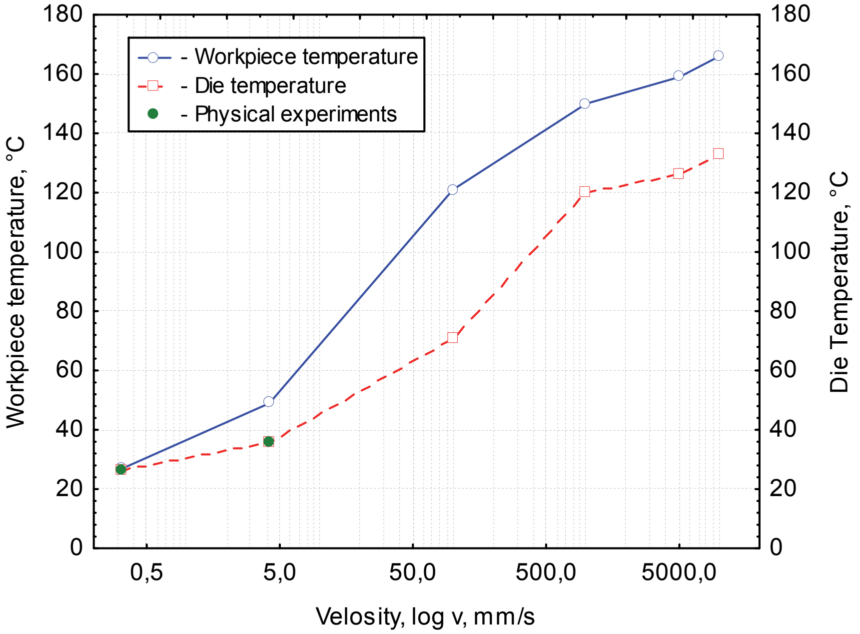


Fig. 6 *Temperature variation at the workpiece with speed (numerical and physical experiments)*

The comparative diagram of maximal temperatures at the die and the workpiece at all the speeds investigated by numerical and physical experiments is shown in Fig. 6. The difference in temperatures at the workpiece and the die presented in Fig. 6 is a consequence of the position where the die temperature was measured in numerical node which is at distance of ≈ 0.3 mm from the die's radius due to comparison with experimental results.

5. CONCLUSION

In this work the temperature distribution in the contact between the die and the workpiece during ironing process has been investigated by physical and numerical analyses. of the. Special attention has been paid to the heat dissipation due to the plastic deformation of material and friction at the tool-workpiece interface. Following conclusions can be drawn from the study:

- Good agreement between physical and numerical results is evident for the temperature values in the tool at the thermocouple position at punch speeds v=0.33 mm/s and v=4.17 mm/s. These data provide good foundation for further numerical estimates of temperatures in the ironing process at high deformation speeds corresponding to industrial conditions;
- With increase of the deformation speed and the increase of temperature occurs in the contact due to the increase of the strain rate and consequently change of the contact friction conditions;
- The established trends of the temperature variations at the workpiece and the tool are different, especially at the beginning of the process, due to the

time needed for the heat conduction from the workpiece to the die;

- Numerical estimates of the temperature at the workpiece at speed of 10000 mm/s that corresponds to manufacturing of 250 cans per minute give the maximum value of temperature of 166°C which is significantly lower than the critical melting temperature of the tin coating providing that the friction in the real process corresponds to conditions of the numerical experiment;

The increased temperature at the interface can significantly influence change of lubricant's characteristics, so it is necessary to take into account the generated heat in the interface, especially at higher deformation speeds, and to enable its transfer from the contact zone by lubricant which at the same time plays the role of coolant.

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