SOME TRIBOLOGICAL ASPECTS OF Fe-Zn COATED STEEL SHEETS AT STAMPING PROCESSES

Emil Evin[1)*], *Miroslav Tomáš*[1)], *Mária Kollárová*[2)], *Bogdan Antoszewski*[3)]
[1)] *Technical University of Košice, Faculty of Mechanical Engineering, Košice, Slovakia*
[2)] *U. S. Steel Košice, s. r. o., 044 54 Košice – Šaca, Slovakia*
[3)] *Kielce University of Technology, 7 Tysiąclecia P. P. Ave, 25-314 Kielce*

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[*]*Corresponding author: Emil Evin, e-mail: Emil.Evin@tuke.sk Tel.: +421 55 602 3547, Department of Technologies and Material, Faculty of Mechanical Engineering, Technical University of Košice, Letná 9, 042 00 Košice, Slovakia*

Abstract
Contribution presents results of study of tribological characteristics of Fe-Zn coated steel sheets. Experimental research was done using coatings with different alloying – under alloyed, optimal and slightly pre alloyed. The optimally alloyed coatings and the slightly prealloyed ones were annealed in order to reach different alloying level. Alloying level was evaluated by phase composition and % Fe in coating. Tribological properties such as surface microgeometry, abrasion, friction coefficient were analysed from the view of formability. Experimental results of strip drawn test were used for verification of strip-drawn test numerical simulation. Based on numerical simulation results, contact pressure on drawing die radius was observed.

Keywords: Fe-Zn coatings, steel sheets, coating morphology, friction coefficient, numerical simulation

1 Introduction

Current production in the automotive, consumer goods industry and also other industries must adapt to many; often mutually conflicting technical, economic and environmental requirements. On the one hand, customer demands for products performance, primarily for safety, reliability, corrosion resistance, driving dynamics, comfort and economy are growing; on the other hand, pressure to reduce emissions, higher productivity, eco-friendly production, reduction of maintenance costs and prices of products is increasing. The main innovative trends for increasing the performance of automobiles include reducing the weight of structural parts that contribute the most to the total weight of the car (body 26 %, 23 % undercarriage, motor 21 %, 22 % equipment, etc.). The effectiveness of this approach has been demonstrated by the results of the project ULSAB. For more than 80% of structural elements of the ULSAB body the builders have used high-strength steels with yield strength from 210 to 550 MPa, ultra-high strength steels with yield strength above 550 MPa, almost half of the weight of the body consists of laser-welded tailored blanks (tailored blanks) and sandwich materials [1,2].
In order to ensure the adequate lifetime of autobodies, majority of structural elements of ULSAB body are made of zinc coated sheets.
Among the coated steel sheets are given the ratio between quality and the price of its irreplaceable galvanized sheets. During annealing after galvanization the transformation of the

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pure zinc (η phase, hcp) to Fe-Zn coating which contains intermetallic δ phases (Zn10Fe, Zn7Fe hexagonal), ζ, phase (Zn13Fe mono-clinic) and Γ phase (Zn10Fe3, bcc) occurs – **Fig. 1**. Phases presented in annealed zinc coating have different properties, this means, that the utility properties (corrosion resistance, abrasion resistance, formability, weldability, and lacquering, etc.) will vary in dependence on phase composition of the coating [3, 4].
According to [5] friction coefficients for zinc coated materials are higher to compare with uncoated sheets. In the contrast to this statement [5], Thomsom [6] states that there are no differences in the behavior of these coatings. Aoki and Doege [7] indicate lower friction coefficient for zinc coated sheets. Similarly, tribological characteristics of laser welded tailored blanks made of the same or different materials with the same or different thickness and surface quality are different. [8].

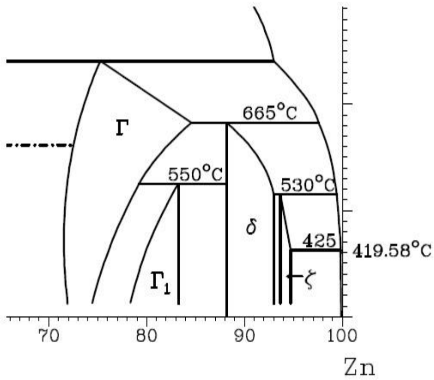

Fig. 1 Equilibrium phase diagram [wt.%]

Scientifically based researches of friction are dated from the 1699 year [9]. Amontons found a direct relationship between normal force and the resulting friction force at the contact surfaces. Charles Coulomb has defined the friction law for relatively low speed, low standard pressure and dry friction [6]: $f = F_f / F_N$, where F_f is the friction force between contact surfaces of the tribological pairs and F_N is the normal force acting on the contact surfaces of the tribological pairs.
The unavoidable consequence of friction is heat that is vented through the inequalities of contact surfaces of die and blank. Due to the fact that the actual contact area between opposite inequalities is considerably smaller than the total contact area (contour area) the high concentration of mechanical energy (friction) and heat occurs in the contacts. In some contact places there is the metal connection – formation of metal bridges – M – (micro welding) [10], [11]. Character of sticking depends on the friction pair. Insoluble metals or metals mutually formed brittle intermetallic phases of small shear strength are those with the best behaviour. Particles of surface inequalities of harder body penetrate into the softer body surface and damage of the softer body surface occurs.
Processes of friction and wear depend not only on the external load of the system, but also on the internal situation in the system, the properties of the lubricant (viscosity, additives and thickness of the coating), microgeometry of sheet metal surface, microgeometry of die surface, the mutual solubility of the material contact surfaces, drawing speed and etc. Selection of appropriate combination of coatings for tribological pair and their surface topology the

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friction, stamping force course, the formation of microwelds, size of sticking, wear of stamping dies and technological characteristics formability (limiting drawing ratios – LDR, hole expansion – HE, limiting dome height – LHD, minimization of number of drawing operations and etc.) can be influenced.

Technological formability of steel sheets depends on their mechanical properties such as microgeometry of contact surfaces, geometry of applied tool and microgeometry of their contact surfaces, pressure of blankholder, applied lubricant, etc. The detailed description of influences of each parameter on technological characteristics is complicated because the individual factors vary due to various situations and as a consequence their influence on technological characteristics of formability varies as well. Applying the simulation we can probably predict the influence of individual factors on characteristics of formability [12-17].

Currently the FEM analyses carried out in production preparation of steel sheet stampings play a very important role and there is increasing tendencies of specification of enter data on material properties and conditions of stamping. These data are mainly connected with the description of material performance model and friction conditions on the contact surfaces of stamping die, e.g. altering of friction ratio of material coupling (steel sheet – stamping die) enables to influence the alteration of plastic deformation, so that in the case of steel with unsatisfactory mechanical properties and as a consequence unsuitable for production of a certain stamping by flat forming applying appropriate microgeometry of tool and sheet or condition of contact surfaces(lacquering, lubricant, etc.) it is possible to achieve improvement of technological formability [8-10]. On the contrary by applying material with excellent formability but both unsatisfactory condition of contact surfaces and microgeometry of the surface could lead to decline of formability.

2 Experimental programme and partial results

2.1 Experimental material and coatings

The properties of Fe-Zn coatings mainly depend on their phase compositions [1, 2]. In general only those coatings are considered as alloyed ones which contain Fe from 8 to 14 %. With higher Fe content in coating there is an increasing tendency to scrolling, on the contrary a lower Fe content in coating such as the alloyed coatings brings about increased ζ phases on the surface which leads to a dramatic increase of friction coefficient. [1, 2]

During the experiment there were used two materials type „galvanneal“ with various iron content in coating – the optimally alloyed coatings and the slightly prealloyed ones (ZnFe 2, ZnFe 3). At the same time we used hot-dip galvanized steel sheet produced from clean metallic zinc and coating of intermetallic phases and therefore it can be considered as underalloyed ZnFe material (ZnFe 1).

Table 1 Properties of Fe-Zn coated materials

Material		**ZnFe 1**	**ZnFe 2**	**ZnFe 3**
Coating thickness [μm]		11,6	7,6	8,0
Total Fe content in coating [%]		5,5	12,6	14,4
Fe-Zn coating nature		low	optimum	prealloyed
Phase composition of coating	cross-section	η, ζ, δ	δ, Γ	δ, Γ
	surface	η	δ	δ
Microhardnes surface phase HV		η (52-72) δ (240-300)		
Parameters *R*a and *P*c	*R*a [μm]	1,3	1,25	1,18
	*P*c [1/cm]	140	120	114

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Annealing after galvanizing changed the parameters *R*a and *P*c. Meeting specific customer requirements were evaluated for changes in the parameters *R*a and *P*c and paint adhesion. Adhesion of Fe-Zn coating depends on % Fe content in the coating [1]. Fe content in the coating in the investigated materials was determined by titration method and phase composition of coatings by Raster Electron Microscopy (REM) with EDX analyser (see **Table 1**). Steel sheets with various iron content in coating were used for experiments on tribological properties. The surface microgeometry parameters of steel sheets were detected on the device Hommel Tester 1000 in the direction of 90° to the rolling direction. The friction characteristics of examined sheets were identified on the tester with plane contact plates and on the curved surface.

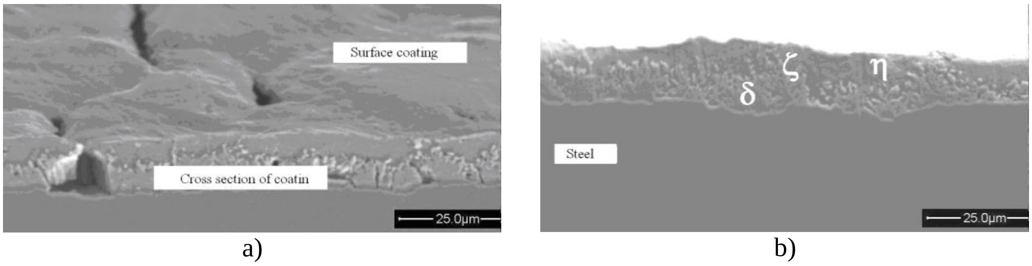

Fig. 2 Microstructure of material ZnFe 1 a) side-view, b) cross section

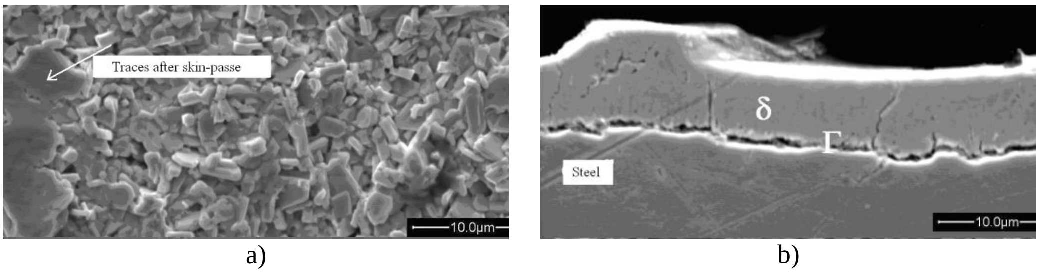

Fig. 3 Microstructure of material ZnFe 2 a) side-view, b) cross section

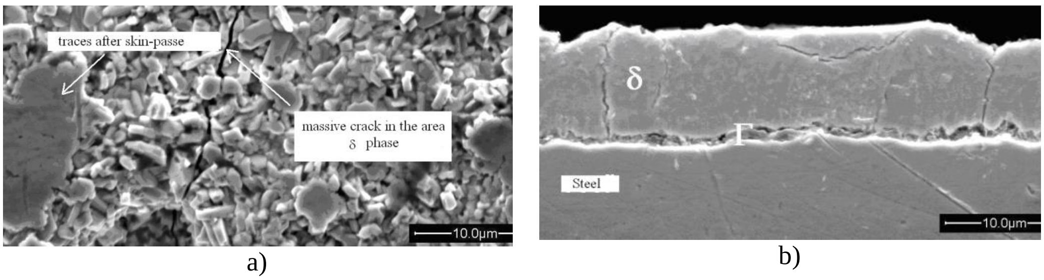

Fig. 4 Microstructure of material ZnFe 3 a) side-view, b) cross section

Concerning the forming aspect none of the samples on the surface contained the undesirable ζ phase. The sample marking and their properties are shown in **Table 1**, microstructure of coatings can be seen in **Fig. 2** to **Fig. 4**. The slightly alloyed material proved the same quality of phase composition as the optimally alloyed one but due to higher Fe content in the coating it showed a thicker layer of Γ phase and there could be observed massive crackings in the area of δ phase.

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Presented coatings were created on IF steel sheet DX54D with material properties shown in **Table 2**.

Table 2 Material properties of zinc coated IF steel sheet DX54 D

Rolling direction	**Yield strength 0,2 % YS [MPa]**	**Ultimate tensile strength UTS [MPa]**	**Material constant K [MPa]**	**Strain hardening exponent n [–]**	**Lanksford's coefficients r [–]**
0°	170	292	492	0,208	1,98
45°	180	304	503	0,203	1,04
90°	184	297	487	0,215	1,59
Average values	182	300	497	0,207	1,59

2.2 Experimental and numerical simulation of friction ratios by strip drawn test

Friction tests as well as modelling of stress state on flat and curved regions at deep drawing were done using the friction simulator shown in **Fig. 5**.

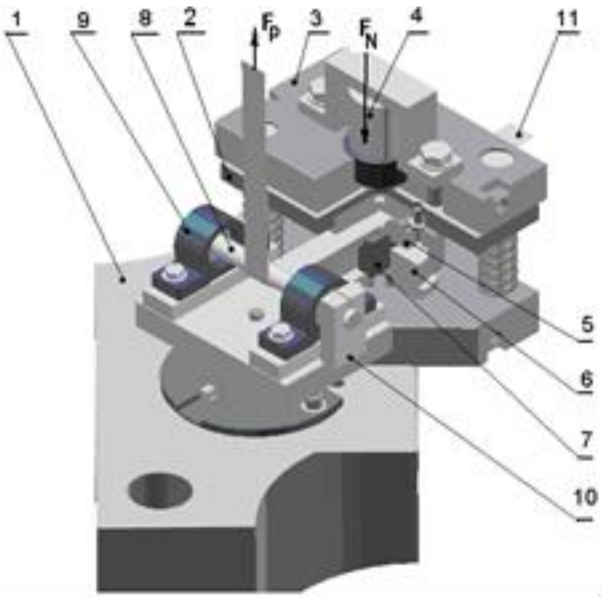

Fig. 5 Model of friction simulator – strip drawing test 1-base plate, 2-middle plate, 3-upper plate, 4-hydraulic clamping cylinder, 5-upper grip, 6-lower grip, 7- dynamometer for measurement of blankholding force, 8-roller, 9-ball bearings, 10- brake mechanism of the roller, 11-strip

The friction simulator enables modelling load of contact surfaces:

1. under blankholder by using a simulator with a rotating roller (f3 = 0),
2. on the die drawing edge by using a simulator with a fixed roller (f3 > 0).

Drawing conditions were as follows: blankholding forces F_N = 4,0 and 9,0 kN, strip drawing speed v = 10 mm/s, roughness of the upper and lower grips Ra = 0,4 μm, roughness of roller Ra

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= 0,4 μm. The surface of steel strip was lubricated with lubricant Anticorit Prelube 3802-39 S with a kinematic viscosity of 60 mm^2/s at 40 °C in the amount of 2 g/m^2.

The first three rows at **Table 3** shows values of adjusted blankholding forces F_N, measured drawing forces Fp(f_3=0) and Fp(f_3>0) and calculated friction coefficients for testing conditions presented in previous. For evaluation of friction coefficient in the area under blankholder were applied analytical Eq. (1) [18-22]:

$$f_{12} = \frac{Fp_{f\,3=0,FN=9} - Fp_{f\,3=0,FN=4}}{2.(FN_{FN=9} - FN_{FN=4})} \tag{1}$$

and the Eq.(2) for calculation of friction coefficient $f3$ on drawing edge of stamping die:

$$f_3 = \frac{2}{\pi}.\ln\left(\frac{Fp_{f\,3>0}}{Fp_{f\,3=0}}\right) \tag{2}$$

Table 3 Calculated friction coefficients – strip drawing with bending

	Blank-holding force F_N [kN]	**Drawing forces**		**Coefficient frictions**	
		State 1 $Fp_{(f3=0)}$ [kN]	State 2 $Fp_{(f3>0)}$ [kN]	$f_{1,2}$ acc. to Eq. (1)	f_3 acc. to Eq. (2)
Experiment – ZnFe 1	4	1,108	1,258	0,113	0,08
	9	2,341	2,646		0,08
Experiment – ZnFe 2	4	1,10	1,262	0,120	0,09
	9	2,29	2,577		0,08
Experiment – ZnFe 3	4	1,10	1,256	0,123	0,08
	9	2,33	2,640		0,08
FEM simulation, $f_{initial}$ = 0,125	4	1,362	1,546		0,08
	9	2,631	-	0,127	
FEM simulation, $f_{initial}$ = 0,110	4	1,246	-		
	9	2,365	2,619	0,117	0,07

Note: State 1 – strip pulling and bending along rotating roller
State 2 – strip pulling and bending along fixed roller

Strip drawn test simulations were realised using software Pam-Stamp2G. Model of experimental device was created in 3D CAD/CAM software Pro/Engineer and its components were exported in neutral format igs. The die geometry was created according to real testing device: drawing die radius 10 mm, flat die part dimensions 30 in length and 50 mm in width (area of blankholder). Meshing of die components and strip were realised in meshing module of Pam-Stamp 2G during models import. Meshed die components are shown in **Fig. 6**. Drawing die was split on two parts in order to simulate different friction conditions under blankholder and drawing radius.

Two states of strip drawing were simulated as it was done during experiment – with a rotating roller (friction coefficient at die radius f_3 = 0) and with a fixed roller (friction coefficient at die radius f_3 > 0). In order to compare experimental results of experiment and simulation were set up blankolding force 4 kN with friction coefficients 0,125 (blankholder) and 0,08 (die radius) and blankolding force 9 kN with friction coefficients 0,110 (blankholder) and 0,07 (die radius).

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These values were chosen based on experimental results of strip drawn test using testing device in Fig. 5.

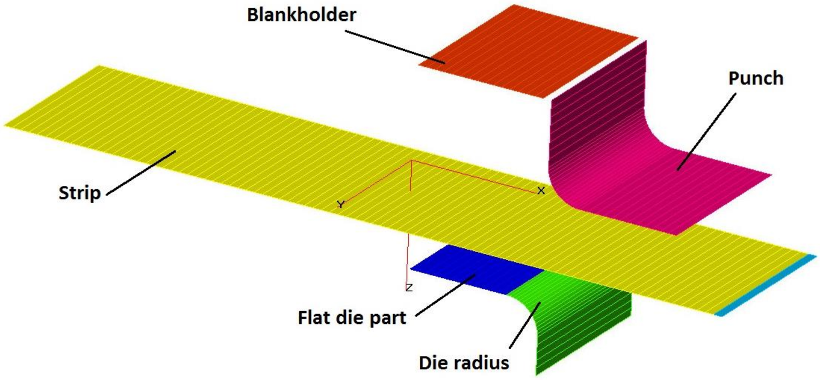

Fig. 6 Set-up of strip drawing simulation – strip bending and pulling

During simulation strip was pulled with velocity 1 m/s applied in corresponding axis. Section force was defined between strip end nodes during simulation and section force element and strip drawing force was then calculated. Blankhoding force in z-direction and "Accurate" contact type were applied during both simulation stages.
Input data for experimental material DX54D was shown in **Table 2**. Holomon's hardening curve was used for hardening definition. As a yield law Orthotropic Hill48 material law was used with Isotropic hardening. Orthothrophic type of material anisotropy was defined by Lankford's coefficients according to measured data shown in **Table 2**. Thickness of material was 0,78 mm.
Results of friction coefficients calculated from simulation according to Eq. (1) and Eq. (2) are shown in **Table 3** at last two rows.

3 Results and discusion

Due to comparison of calculated average values of friction coefficients as shown in **Fig. 7** it follows that the underalloyed material proved the lowest values of friction coefficients it means this is the material with remanent clean metallic zinc on the surface (ZnFe 1). The zinc coating of the material ZnFe 1 has a better lubricating ability than the coatings of the materials ZnFe 2 and ZnFe 3, but during forming the tools are contaminated and there arise glide paths on their surfaces and it could lead to damage of lacquer of automobile chassis. In the case of alloyed and overalloyed materials ZnFe 2 and ZnFe 3 with a higher Fe content in the coating there were increased values of friction coefficients f_{12} and f_3 see **Fig. 7**.
The increased friction coefficient is a consequence of higher abrasiveness caused by δ phase on the surface of material. It is necessary to note that there were not identified significant differences in friction coefficients among various coatings. Concerning weldability the underalloyed coatings do not possess the advantage of steel sheets with Fe-Zn coatings therefore the final assessment of phase composition of coating and of obtained friction coefficients favours the optimally alloyed material.
Unlike the clean metallic coatings the alloyed ones type „galvanneal" (ZnFe 2, ZnFe 3) are much more harder. The microhardness of major δ phase in ZnFe coating compared with clean metallic zinc is 6 times higher: clean metallic Zn – approximately 50, δ phase – approximately

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300 HV (10 g); on the other hand it can cause damage of stamping tools. Therefore during production of stampings from these materials it is advisable to focus on lubrication. The

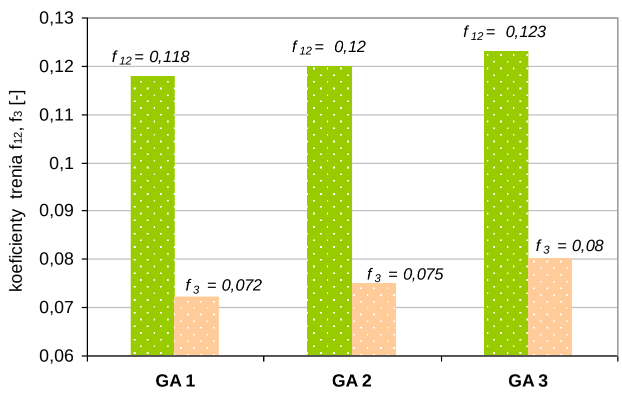

Fig. 7 Values of friction coefficient under the blankholder and on the drawing edge for individual coatings

tribological properties (friction, depreciation) of sheets type „galvanneal“ differ from those of classical steel sheets designed for deep drawing meaning that the lubricant suitable for classical steel sheets need not be suitable for sheets with certain surface treatment. The material type “galvanneal” presents in many aspects a progressive material but utilization of its significant properties requires optimization of forming procedure, or the choice of the lubricant. The processes of forming and lubrication also bring about a deeper insight into damage of Fe-Zn layers in different types of coatings. Further research will be carried out in the field ofcomparison of size of abrasion which mainly depends on mechanical properties, microstructure of the surface, structure and composition of ZnFe layers and on requirements of forming. According to paper [3, 4] the abrasion of steel sheets type „galvaneal“ will be propably higher than of those with clean metallic zinc coating.

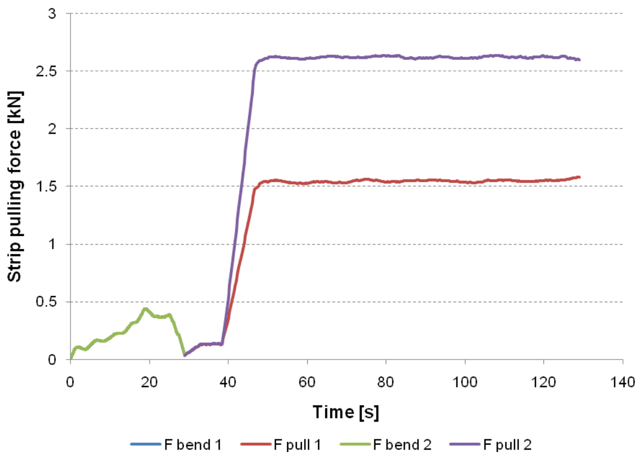

Fig. 8 Graphs showing strip bending and pulling force at different friction and holding conditions a) F_N = 4 kN; $f_{1,2}$ = 0,125; f_3 = 0,08 b) F_N = 9 kN; $f_{1,2}$ = 0,11; f_3 = 0,07

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Comparing the friction coefficients calculated from experimentally measured data (see **Table 3**), better conformity was reached between friction coefficients computed from strip pulling force values according to eq. (2) than according to eq. (1). The advantage of eq. (2) is, the friction coefficient is computed from ratio of pulling and blankholding force differences, what eliminates the influence of some factors (bending force influence, friction in bearings etc.) to pulling force. By comparing friction coefficients on die radius computed according to eq. (2) from experimental measured and FEM simulation results were reached difference approx. 7 %.

The contact pressures on drawing die radius as results of strip drawing simulation are shown in **Fig. 8**, **Fig. 9** and **Fig. 10**. When blankholding force was set to 4 kN, contact pressure between blankholder and steel sheet was 2,5 to 3 MPa with maximal value 23 MPa at drawing die radius at wrapping angle 62° - see **Fig. 9**. Similar results were observed with blankholder force set to 9 kN – contact pressure between blankholder and steel sheet was 6 MPa with maximal value 32,3 MPa at drawing die radius at wrapping angle 62°. From measured values of friction coefficients under blankholder follows, that lower values of blankholder pressure gives lower values of friction coefficients as higher pressures on drawing die radius. We assume Anticorit Prelube 3802-39 S includes high-pressure additives and its efficiency increases with pressure rising.

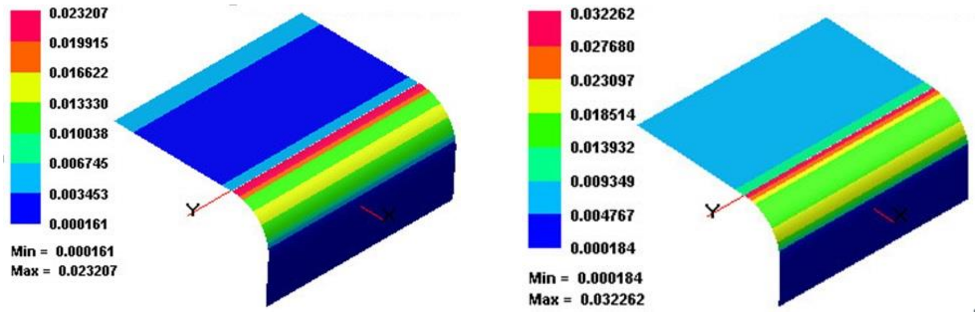

Fig. 9 Normal contact pressure during strip drawing simulation a) F_N = 4 kN; $f_{1,2}$ = 0,125; f_3 = 0,08 b) F_N = 9 kN; $f_{1,2}$ = 0,11; f_3 = 0,07

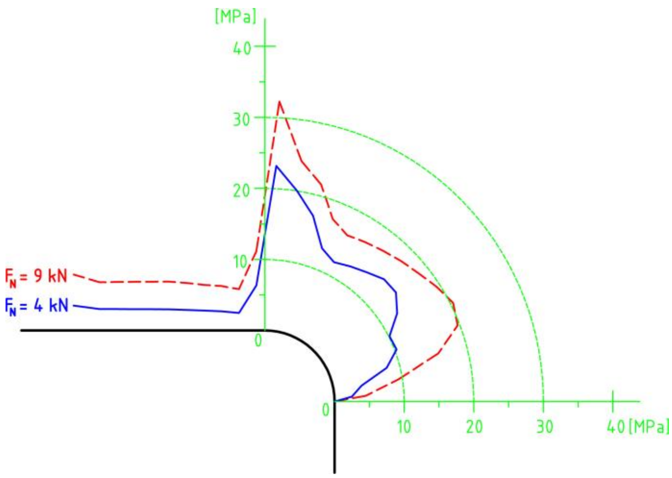

Fig. 10 Course of normal contact pressure along flat die part and die radius

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4 Conclusions

The paper presents determination of the friction characteristics of steel sheets with various Fe-Zn coatings. Due to small differences in friction coefficients and considering conditions of weldability, formability, etc. of different coatings we can say, the final assessment favours the optimally alloyed material. The material type "galvanneal" presents a very progressive material in many aspects but it is advisable to optimize the process of forming to be able to utilize all its properties. Comparing friction coefficients calculated from experimentally measured data and from numerical simulation in PAM STAMP 2G simulation software the very good conformity has been proven. Further research will be carried out in the field of damage of Fe-Zn layers in different types of coatings at forming in order to compare size of abrasion, which mainly depends on mechanical properties, microstructure of the surface, structure and composition of ZnFe layers and on requirements of forming.

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