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STUDY OF Fe-Zn COATED STEEL SHEETS TRIBOLOGICAL CHARACTERISTICS

STUDIUM CHARAKTERYSTYK TRIBOLOGICZNYCH BLACH STALOWYCH Z POWŁOKAMI Fe-Zn

Key words:

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

Słowa kluczowe:

powłoki Fe-Zn, blachy stalowe, mortologia powłoki, współczynnik tarcia, symulacja numeryczna

Summary

This paper presents the results of a study of the 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 alloying level was evaluated by phase composition and the percentage of Fe in the coating. Tribological properties such as surface microgeometry, abrasion, and friction coefficient were analysed. The experimental results of strip drawn

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test were used for the verification of numerical simulation. Based on numerical simulation results, characteristics has been determined.

INTRODUCTION

Increasing demands on the anticorrossion behavior of steel sheet stampings in the automotive industry support the development of various types of coated steel sheets. The coated steel sheets are evaluated by the ratio between quality and the price of its irreplaceable galvanized sheets. Unlike conventional steel sheets, the evolution of galvanized steel sheets has its own characteristics for the automotive industry. Requirements must be met for the mechanical properties and to ensure a perfect surface zinc coating and adhesion to the base materials. To achieve the desired surface appearance of body parts after pressing and after painting, customers require very close tolerance parameters Ra with a uniform microgeometry surface. Galvanized steel sheets designed for surface parts are mainly focused on parameters of roughness Ra and Pc [cm^{-1}] (number of peaks) **[L. 1, 2]**.

Technological formabilities of steel sheets depend on their mechanical properties such as the microgeometry of contact surfaces, the geometry of the applied tools and the microgeometry of their contact surfaces, the pressure of blankholder, the applied lubricant, etc. The detailed description of influences of each parameters 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 may predict the influence of individual factors on the characteristics of formability **[L. 3–7]**.

Currently, the FEM analyses carried out in production preparation of steel sheet stampings play a very important role, and there are increasing tendencies for the specification of data recorded on the material properties and conditions of stamping. Data are mainly connected with the description of material performance models and friction conditions on the contact surfaces of the stamping die, e.g., altering the friction ratio of material coupling (steel sheet – stamping die) that influences the alteration of plastic deformation. Therefore, in the case of steel with unsatisfactory mechanical properties which are unsuitable for the production of a certain stamping by flat forming, while applying appropriate microgeometry of the tool and sheet or the condition of contact surfaces (lacquering, lubricant, etc.), it is possible to achieve an improvement in technological formability **[L. 8–10]**. On the contrary, applying material with excellent formability but with an unsatisfactory condition of contact surfaces and microgeometry can lead to a decline in formability.

EXPERIMENTAL PROGRAMME AND PARTIAL RESULTS

Experimental material and coatings

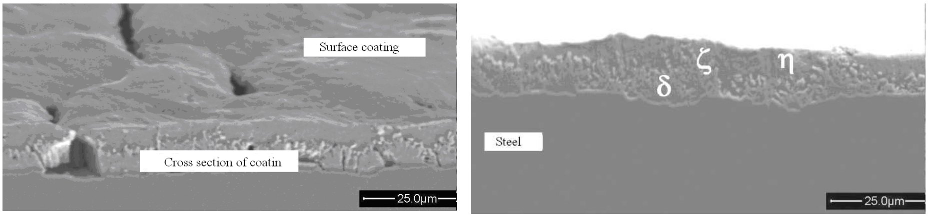
The properties of Fe-Zn coatings mainly depend on their phase compositions **[L. 1, 2]**. In general, only those coatings are considered alloyed which contain Fe from 8% to 14%. With higher Fe content in coating there is an increasing tendency for scrolling. On the contrary, a lower Fe content in a coating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

During the experiment two material types of "galvanneal" with various iron content in the coating were used – the optimally alloyed coatings and the slightly prealloyed ones (GA 2, GA 3). At the same time, we used hot-dip galvanized steel sheeting produced from clean metallic zinc and a coating of intermetallical phases, which can be considered as underalloyed GA material (GA 1).

Annealing after galvanizing changed the parameters Ra and Pc. Specific customer requirements were evaluated for changes in the parameters Ra and Pc and paint adhesion. Adhesion of Fe-Zn coatings depends on the percentage of Fe content in the coating **[L. 1]**. Fe content in the coating in the investigated materials was determined by titration, and the phase composition of coatings was determined by Raster Electron Microscopy (REM) with EDX analyser (see **Tab. 1**). Steel sheets with various iron content in the coating were used for experiments on tribological properties. The surface microgeometry parameters of steel sheets were detected on a 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.

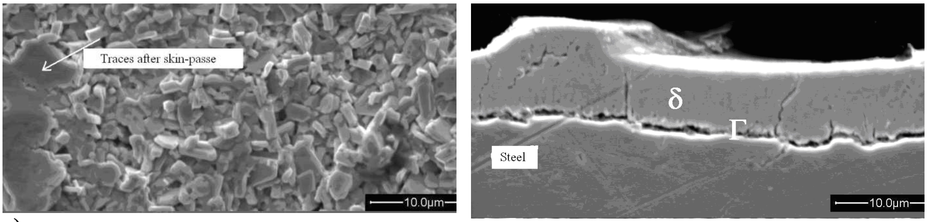
Table 1. Properties of Fe-Zn coatings materials
Tabela 1. Własności powłok Fe-Zn

Material		GA 1	GA 2	GA 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, Γv	δ, Γ
	surface	H	Δ	Δ
Microhardnes surface phase HV		η (52-72) δ (240-300)		
Parameters Ra and Pc	Ra [µm]	1.3	1.25	1.18
	Pc [1/cm]	140	120	114



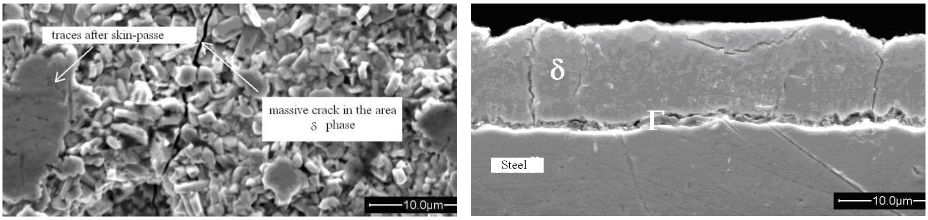
a) b)

Fig. 1. Microstructure of material GA 1: a) side-view, b) cross section
Rys. 1. Mikrostruktura materiału GA 1: a) widok, b) przekrój



a) b)

Fig. 2. Microstructure of material GA 2: a) side-view, b) cross section
Rys. 2. Mikrostruktura materiału GA 2: a) widok, b) przekrój



a) b)

Fig. 3. Microstructure of material GA 3: a) side-view, b) cross section
Rys. 3. Mikrostruktura materiału GA 3: a) widok, b) przekrój

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 **Tab. 1,** microstructure of coatings can be seen in **Figs. 1** to **3**. The slightly alloyed material proved to have 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 the Γ phase and massive crackings in the area of δ phase could be observed.

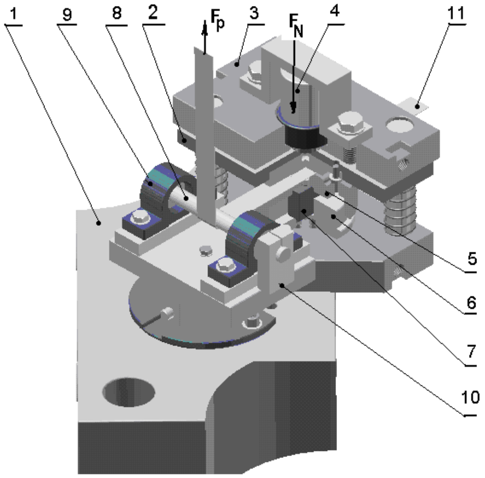
The presented coatings were created on a IF steel sheet DX54D with material properties shown in **Tab. 2.**

Table 2. Material properties of DX54 D – zinc coated IF steel sheet
Tabela 2. Własności materiału DX54 D – blachy stalowej IF z powłoką cynku

Rolling direction	Yield strength 0,2% YS [MPa]	Ultimate tensile strength UTS [MPa]	Material constant K [MPa]	Strain hardening exponent n [-]	Lanksford's coefficients [-]
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

Experimental and numerical simulation of friction ratios by strip drawn test

Friction tests as well as modelling of the stress state on flat and curved regions at deep drawing were done using the friction simulator shown in **Fig. 4.**



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

Fig. 4. Model of friction simulator – strip drawing test
Rys. 4. Model symulatora tarcia – test paskowy

The friction simulator enables the modelling load of contact surfaces:

1. Under blankholder by using a simulator with a rotating roller ($f_3 = 0$),
2. On the die drawing edge by using a simulator with a fixed roller ($f_3 > 0$).

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 = 0.4 µm. The surface of the 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 in **Tab. 3** show the values of adjusted blankholding forces F_N, measured drawing forces $F_{p(f3=0)}$ and $F_{p(f3>0)}$ and the calculated friction coefficients for testing conditions presented previously. For evaluation of the friction coefficient in the area under the blankholder, analytical Eq. (1) was applied **[L. 9–12]**:

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

Eq. (2) was applied for the calculation of friction coefficient f_3 on the 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
Tabela 3. Obliczone wartości współczynnika tarcia – test paskowy ze zginaniem

	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 rel. (1)	f_3 acc. to rel. (2)
Experiment – GA1	4	1.108	1.258	0.113	0.08
	9	2.341	2.646		0.08
Experiment – GA2	4	1.1	1.262	0.12	0.09
	9	2.29	2.577		0.08
Experiment – GA3	4	1.1	1.256	0.123	0.08
	9	2.33	2.64		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. The model of the 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 a real testing device as follows: 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 the strips were realised in the meshing module of Pam-Stamp 2G during model import. Meshed die components are shown in **Fig. 5**. The drawing die was split into two parts in order to simulate different friction conditions under blankholder and drawing radius.

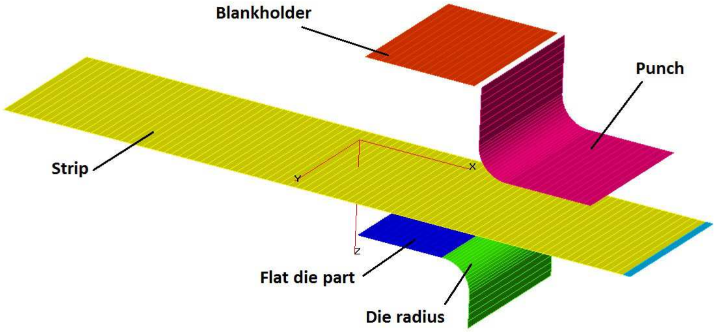


Fig. 5. Set-up of strip drawing simulation - strip bending and pulling
Rys. 5. Konfiguracja symulacji paskowej – zginanie i przeciąganie

Two states of strip drawing were simulated. During the experiment, the simulation was done 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 the experiment and simulation, 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) were set up. These values were chosen based on experimental results of strip drawn test using the testing device in **Fig. 4.**

During simulation, the strip was pulled with a velocity of 1 m/s applied in the corresponding axis. Section force was defined between the strip end nodes during simulation, and the section force element and the strip drawing force were then calculated. The blankholding force in the z-direction and an “Accurate” contact type were applied during both simulation stages.

Input data for experimental material DX54D are shown in **Tab. 2**. Holomon’s hardening curve was used for hardening definition. An Orthotropic Hill48 material yield law was used with isotropic hardening. The orthothrophic type of material anisotropy was defined by Lankford’s coefficients according to measured data shown in **Tab. 2.** The thickness of material was 0.78 mm.

The results of calculated friction coefficients from the simulation using Eq. (1) and Eq. (2) are shown in **Tab. 3** in the last two rows.

RESULTS AND DISCUSSION

Due to the comparison of calculated average values of friction coefficients as shown in **Fig. 6**, it follows that the underalloyed material proved to have the lowest values of friction coefficients. This means that this is the material with remanent clean metallic zinc on the surface (GA1). The zinc coating of the material GA 1 has a better lubricating ability than the coatings of the materials GA 2 and GA 3; however, during forming, the tools are contaminated, and glide paths arise on their surfaces that can lead to damage of the lacquer of the automobile chassis. In the case of alloyed and overalloyed materials GA 2 and GA 3 with a higher Fe content in the coating, there were increased values of friction coefficients f_{12} and f_3 (see **Fig. 6**). The increased friction coefficient is a consequence of the higher abrasiveness caused by the δ phase on the surface of the material. It is necessary to note that there were no 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 the obtained friction coefficients favours the optimally alloyed material.

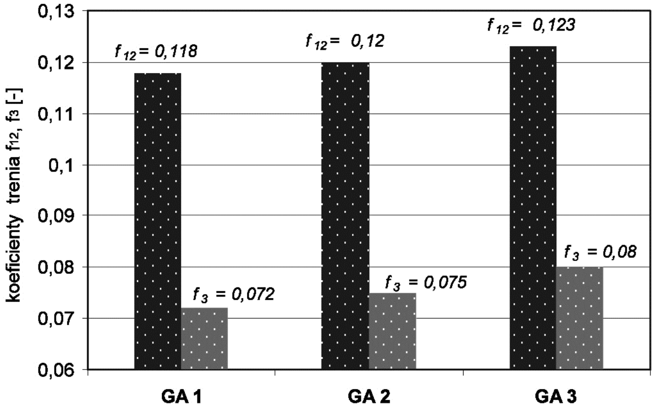


Fig. 6. Values of friction coefficient under the blankholder and on the drawing edge for individual coatings

Rys. 6. Wartości współczynnika tarcia pod uchwytem i na krawędzi przeciągania dla różnych powłok

Unlike the clean metallic coatings, the alloyed type "galvanneal" (GA 2, GA 3) are much harder. The microhardness of the major δ phase in GA coatings is six times higher than clean metallic zinc [clean metallic Zn – approximately 50, δ phase – approximately 300 HV (10 g)]. On the other hand, it can cause damage to stamping tools. Therefore, during the production of stampings from these materials, it is advisable to focus on lubrication. The tribological properties (friction, depreciation) of “galvanneal” sheets differ from those of classical steel sheets designed for deep drawing, which means that the lubricant suitable for classical steel sheets need not be suitable for sheets with certain surface treatments. The “galvanneal” material type presents a progressive material in many ways, but the utilization of its significant properties requires the optimalization of forming procedure, e.g. 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 of the comparison of the size of abrasion, which mainly depends on mechanical properties, the microstructure of the surface, structure, the composition of GA layers, and on the requirements of forming. According to papers **[L. 3, 4]**, the abrasion of steel sheets type “galvanneal” will probably be higher than of those with clean metallic zinc coating.

Results of strip drawing simulation are shown in **Fig. 7, 8,** and **9**. When the blankholding force was set to 4 kN, contact pressure between the blankholder and the steel sheet was 2.5 to 3 MPa with a maximum value of 23 MPa at drawing die radius at a wrapping angle of 62° (See **Fig. 9**). Similar

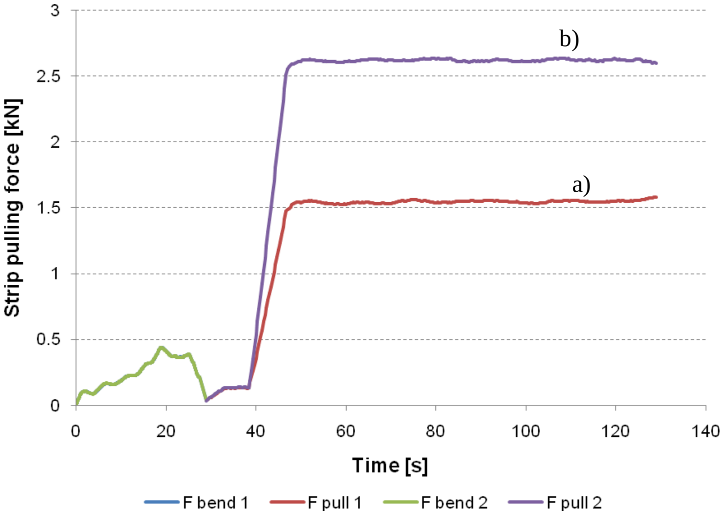


Fig. 7. Graphs showing strip bending and pulling force at different friction and holding conditions: a) $F_N = 4$ kN; $f_{1,2} = 0.125$; $f_3 = 0.08$, b) $F_N = 9$ kN; $f_{1,2} = 0.11$; $f_3 = 0.07$

Rys. 7. Diagramy z testu paskowego dla różnych warunków testowania: 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

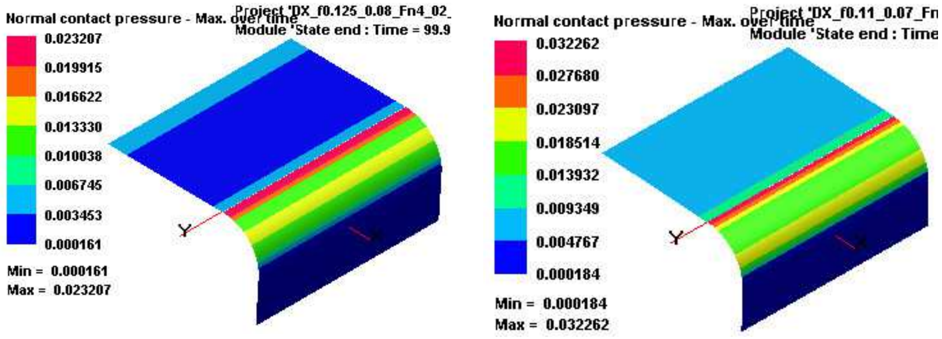


Fig. 8. Maximum normal contact pressure during strip drawing simulation: a) F_N = 4 kN; $f_{1,2}$ = 0.125; f_3 = 0.08; b) F_N = 9 kN; $f_{1,2}$ = 0.11; f_3 = 0.07

Rys. 8. Maksymalne naciski stykowe podczas symulacji przeciągania paska: 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

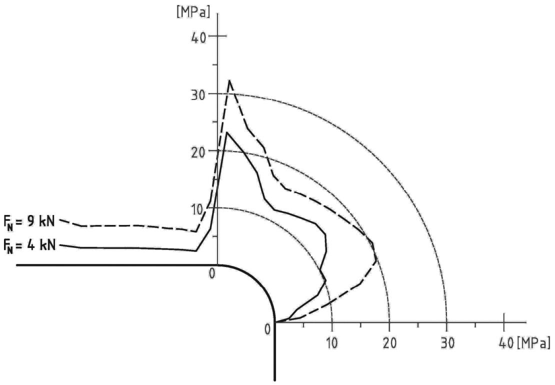


Fig. 9. Distribution of the normal contact pressure along flat die part

Rys. 9. Rozkład nacisków normalnych na płaskiej części matrycy

results were observed with the blankholder force set to 9 kN - contact pressure between blankholder and steel sheet was 6 MPa with a maximum value of 32.3 MPa at drawing die radius at a wrapping angle of 62°. From the measured values of friction coefficients under blankholder, we can conclude that lower values of blankholder pressure give lower values of friction coefficients with higher pressures on the drawing die radius. We assume Anticorit Prelube 3802-39 S includes high-pressure additives, and its efficiency increases with rising pressure.

SUMMARY

The aim of this paper was to determine the friction chracateristics of steel sheets with various Fe-Zn coatings. Steel sheets with various iron content coatings were used to perform formability tests. The friction characteristics of examined steel sheets were identified on the tester with plane contact plates and on the curved surface.

1. Various kinds of materials of GA with increasing iron content in the coating showed a variation in the values of friction coefficients. The lowest coefficients, f_{12} and f_3 were observed in underalloyed material with clean metallic zinc on the surface. On the other hand, the highest values were observed in overalloyed material due to the presence of the δ phase on the surface of the material. The increase in the values of friction coefficients is connected with an increase in the hardness of optimally alloyed material, e.g., of overalloyed materials compared with those containing clean metallic zinc on the surface. Due to small differences in friction coefficients, and considering conditions of weldability, formability, etc. of different types of coatings, we can say that the final assessment favours the optimally alloyed material. The "galvanneal" material type presents a very progressive material in many aspects, but it is advisable to optimalize the process of forming to be able to to utilize all its properties.
2. Better conformity was reached between friction coefficients computed from strip pulling force values according to Eq. (2) than according to Eq. (1), taking into account friction coefficients computed from experimentally measured pulling and blankholding forces. The advantage of Eq. (2) is that the friction coefficient is computed from the ratio of pulling and blankholding force differences, which eliminates the influence of some factors (bending force influence, friction in bearings, etc.) to pulling force.
3. By comparing friction coefficients on die radius computed according to Eq. (2), from experimentally measured values, the FEM simulation results were reached a difference of approx. 7%. This indicates that the friction model described by Eq. (2) for drawing die radius implemented in PAM STAMP 2G simulation software is in very good conformity to experimental measured results.

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Streszczenie

Artykuł przedstawia wyniki badań charakterystyk tribologicznych blach stalowych z powłokami Fe-Zn. Badania eksperymentalne zostały wykonane dla powłok o różnym składzie stopu – z niską zawartością żelaza, o składzie optymalnym i z powłoką wstępną. Tworzenie stopu było oceniane przez kompozycję fazową i zawartość procentową Fe w powłoce. Własności tribologiczne, jak mikogeometria powierzchni, zużycie ścierne, współczynnik tarcia były analizowane z punktu widzenia formowalności. Wyniki testów paskowych posłużyły do weryfikacji symulacji numerycznej tego testu. Na bazie wyników symulacji numerycznej określono naciski stykowe na promieniu matrycy ciągowej.