VARIABLE TRIBOLOGICAL CONDITIONS ON THE FLANGE AND NONMONOTONOUS FORMING IN DEEP DRAWING OF COATED SHEETS

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ABSTRACT

In the paper are presented results of experimental investigation of influences of specific tribological system during the nonmonotonous two-phase process of deep drawing of low carbon electro-galvanised steel sheets. The piece geometry is prismatic, with rectangular cross-section. In the first phase of forming the uniaxial tension is done of the wide stripes, until the elongation is 10%, after that the blank is produced and then deep drawing as the second phase. The flange zone is considered where the friction regimes are created in three ways: dry surfaces, application of the adequate oil, application of the oil and the PET foil. The normal force, i.e. the blank holding force, is being set based on conditions of the constant contact pressure that requires possibility of creating the variable blank holding force with decreasing character, according to the flange decrease during the forming process. The other influences: speed, friction conditions in the other zones outside of the flange, tools, etc., were not varied.

Identification and estimate of the influences of some tribological parameters are done by monitoring the drawing force, the distribution of the main strains in the sheet plane, their relation to the limiting formability curves, as well as the drawing depth.

It was concluded that it is possible to use the concrete nonmonotonousness and the adequate combinations of the piece position, the friction regime and the contact pressure on the flange and in that way to improve the process results.

Keywords: friction on the flange, nonmonotonous forming, coated sheets, deep drawing.

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Deep drawing of thin sheets represents one of the dominant technologies in modern industry. Of all the materials the most frequently applied are the low-carbon steel sheets due to their good combination of strength, formability, recycling capacity and price. The main deficiency of those sheets is the low corrosion resistance. Due to that, the whole series of sheets was developed with the same substrate and with various anticorrosion coatings on one or both sides. The largest applications have the electrochemical, galvanic coatings based on zinc (Zn). The previous statements are confirmed by data on manufactured quantities of thin sheets[1]. For instance[1], the estimated manufacturing only of thin sheets with coatings, at a global level, for year 2006, amounts to cca. 110 million t.

The deep drawing process carries a series of specifics[1,2]: the contact pressures are significantly below the yield strength; the friction is not always damaging – it does not have to be lowered always; the type of material, chemical composition, tribological characteristics, mechanical characteristics, formability, etc. are most frequently sets according to the prescribed criteria that are not related to tribological requirements, like the painting adherence; limited material selection, etc. All enumerated represent the significant differences with respect to the tribological phenomena in contacts of the rigid machine parts.

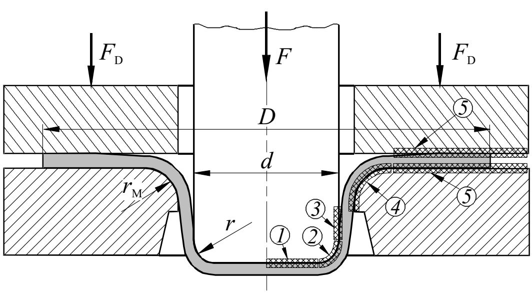

Fig. 1. Friction zones in deep drawing

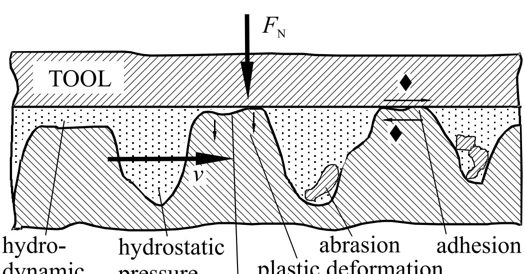

Fig. 2. Contact between die and sheet on microlevel

The most important friction zones are shown in Fig. 1. If the friction was eliminated from zone 4 (the die radius zone), the forming force could be decreased up to 20% (Ref. 3). By eliminating friction from zone 5 (the flange zone) the punch force can be decreased even more than 50% (Ref. 2). In this paper the attention was devoted to flange zone 5. The conclusion was adopted that in zone 5 the contact of the flat surfaces is realised and kept until the end of the process[3].

The analysis of contact at a microlevel in real conditions (Fig. 2) points to all the complexity of tribological phenomena. Different phenomena appear: particles abrasion, hydrodynamic effects (especially at higher sliding speeds), forming of pockets with hydrostatic pressure and elimination of friction, very prominent plastic deformation of asperity peaks, etc.[4,5] By inspection of surfaces on the piece flange, the flattening of roughness was noticed that leads to increase of the contact surface and decrease of the contact pressure from the calculated values through 300 MPa (Refs 4 and 5) on a microlevel, to the real values below 10 MPa at a macrolevel. In practice, the friction regime in deep drawing is almost always mixed or boundary[3] (except for the special forming processes[6]). Rarely appears the case when the total load is transferred through the lubricant, which completely separates the contact surfaces with significantly decreased friction. The dry friction regime (transfer of load exclusively through the metal contact) does not exist in industrial practice, but in the research sense it is significant as the source of the referent values of corresponding characteristics.

In the last decade, the significant research and expert effort was put to obtain, besides the purely scientific tribological knowledge, also concrete technological results, related to the control of the deep drawing process during its course. It turned out[7] that the possibilities are very limited to influence that process. Namely, it is possible only to influence the friction on the flange via one of the tribological parameters – the blank holding force (i.e. the contact pressure) and via the draw bead of the variable geometry[6]. Different devices were developed[8,9], frequently very complex and expensive[9]. The common denominator of this research and the previously mentioned is in using the variable intensity of the blank holding force (BHF). Namely, in order to realise the condition of constant contact pressure on the flange, the BHF should decrease according to decrease of the piece flange surface. In experimental sense, this imposes the necessity for more complex devices.

In the authors research, in the past few years[10–14], the attempt was made to analyse the combined action of various tribological parameters (friction regimes, working pieces materials, distribution of the contact pressure on the flange during the process, piece geometry) with realisation of single-operation monotonous and two-phase nonmonotonous forming process.

EXPERIMENTAL

DESCRIPTION OF EXPERIMENT AND USED EQUIPMENT

The essence of the experiment is to realise the combined action of two-phased nonmonotonous process of plastic forming and tribological factors. The corresponding operations of the monotonous process of plastic forming were realised with variation of parameters that influence the tribological processes in the piece flange contact zone. The normal force and the lubrication regimes were varied. Three versions of the normal force and the friction regimes were applied. The following parameters were not varied: the strain rate, the friction conditions in the zones outside the flange, galvanic Zn-coating on the thin sheet and the tool geometry. The piece geometry is box-like with a square cross-section 40×40 mm. It is obtained from the circular blank with 100 mm diameter. Analysis of the realised effects was monitored through plastic forming process parameters: the process deformation forces, distribution of the main surface strains and their relation to the forming limit diagrams (FLD) as well as the drawing depth. Experimental methodology and the used equipment[10–12], represent relatively complex system and here will be presented only in a very shortened form.

The first operation of the forming process – the prior preparatory forming, was done on a classical machine for mechanical testing with the corresponding tool for prior uniaxial tension of the sheets stripes[10]. The initial gauge length of stripes is 500 mm, while the width is 130 mm. The sheet thickness is 0.8 mm (DC04+ZE according to DIN EN 10152). The tension was done all the way until the plastic strain of 10% was reached. That amount of strain was chosen, because then the material deformability is not significantly decreased, while the area of plasticity is entered.

For deep drawing of the previously deformed samples of thin sheet was used an advanced laboratory hydraulic press with triple action ERICHSEN 142/2 (Fig. 3). The maximum force of the main action – 130 kN, the maximum holding force – 34 kN, and the main action speed range is 0–250 mm/min. The basic version of the laboratory press was improved by the data acquisition system, which, during the course of the process, enables the following: measurement of the deformation force, measurement of the normal force (holding force), control of the holding force (by setting the variable intensity according to the previously defined dependence in analytical form). All operations were done at a constant

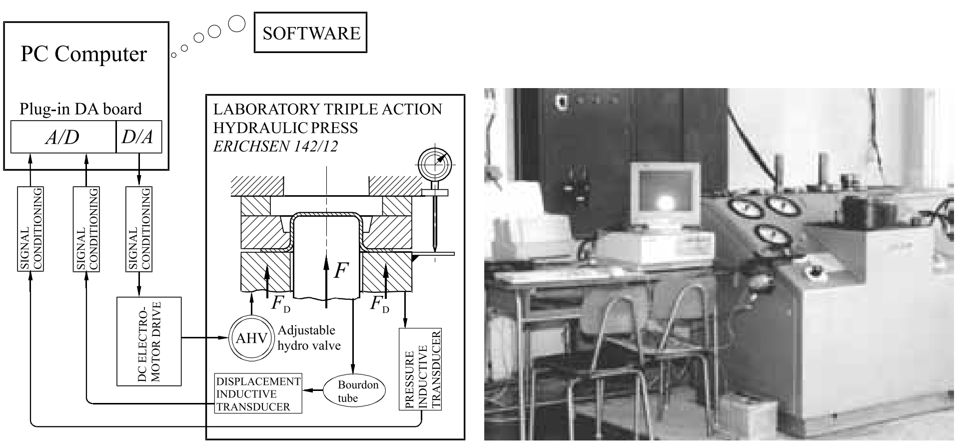

Fig. 3. Experimental device scheme (left) and physical view (right)

speed of the punch of 20 mm/min. The appearance of wrinkles on the flange was registered mechanically. For measurement of deformation, the classical method of circular grid measurement was applied, which assumes applying the grid of small circles of 3 mm diameter and straight lines passing through the circles centers. On all the parts the grid was applied electrochemically (device ERICHSEN of power 1.5 kW). Measurement of the deformed grid was done in optical way[10].

In Fig. 3 is shown the block-scheme of the most important parts of the acquisition system.

DEFINING OF THE HOLDING FORCE

In preparation of the experiment it is necessary to define the complete procedure for determination of the holding force (the normal force on the flange), i.e. the contact pressure.

The first way is to define the constant value of the force based on empirical recommendations. Usually recommendations provide the value of the holder specific pressure (q), based on which, by multiplying the initial flange area, is obtained one of the most important technological parameters – the holding force. The unwanted effect of the constant holding force is unnecessary high increase of pressure q at the end of the punch travel. In the concrete case, the three empirical formulae were selected for determination of the pressure q and the average value was calculated[10]. It carries the notification R (recommendation). The obtained value[10] is q = 2.287 MPa, thus the holding force is F_D = 12992.3 N.

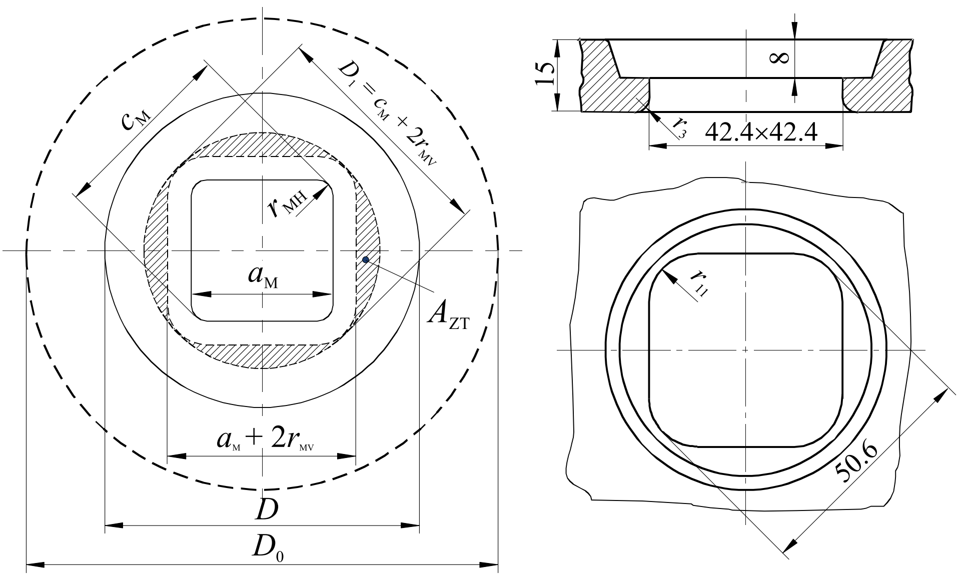

Fig. 4. Flange area changing (left) and die geometry (right)

The second way of defining the constant holding force F_D represents the specific optimisation by a special experiment, through the wrinkles-fracture diagram according to criterion of the largest drawing depth. To the maximum drawing depth corresponds the most favourable value of F_D. The force F_D defined in this way is denoted as E (experimental optimisation). From Fig. 5*a* the value of optimum force was determined as F_D = 9.5 kN for the (O) friction regime. From Fig. 5*b*, the obtained values are F_D = 1.5 kN (D), F_D = 4.5 kN (O) and F_D = 15 kN (O+F).

The intensities of the constant force F_D were defined in the two previously mentioned ways, where the emphasis is on the R version. The third procedure assumes respecting the conditions of the constant value of the holder constant pressure q during the course of deep drawing process.

The relation between the holding force F_D and the specific pressure q represents the piece flange area. It varies from the maximum value at the beginning of the process to zero at the end. Here is adopted that the final geometry represents the box-like form of the square cross-section without the flange. The drawing tool has dimensions 40×40 mm with a rounding radius of 4 mm in the vertical and 10 mm in the horizontal plane. The blank is of circular form with 100 mm diameters. If a constant rate of deformation and continuous course of the process (that corresponds to reality) are accepted, it is possible to come up with the functional dependence of the flange area on time and the punch travel. In Fig. 4 are shown the geometry of the die and the scheme of the piece flange variation.

Satisfying the condition of constant specific pressure q, it is assumed that the holding force F_{Dt} intensity should be decreasing proportionally with the variation of the piece flange area A_{FLt}, depending on the time or the punch step.

$$F_{Dt} = qA_{FLt},\ q = \text{const} \tag{1}$$

The blank in this experiment was circular, with diameter D_0 (Fig. 4). During the process, the circular shape of the flange is being disturbed, so at the end there is no area A_{ZT} (Fig. 5). To account for that, A_{Zt}, the variation of the area of the circular shaped flange was introduced as a function of time (t), which approximately represents the difference between the ideal circular area and the real flange area. At the beginning $A_{Zt} = 0$ and at the end of the process $A_{Zt} = A_{ZT}$. The assumption as also adopted of the linear variation of the area A_{Zt} and diameter D (expressions (4) and (5)). Time T_1 is the total time of the deep drawing process duration and it is determined by the previous test.

The instantaneous real flange area can be expressed in the following way:

$$A_{FLt} = \frac{\pi}{4}\left(D^2 - D_1^2\right) + A_{ZT} - A_{Zt}. \tag{2}$$

According to Fig. 4, the following constant values are obtained:

$$A_{ZT} = \frac{D_1^2\pi}{4} - \left[\left(a_M + 2r_{MV}\right)^2 - \left(4r_D^2 - r_D^2\pi\right)\right] = \text{const.} \tag{3}$$

$$r_D = r_{MH} + r_{MV} = \text{const}; D_1 = c_M + 2r_{MV} = \text{const}.$$

$$D = D_0 - \frac{D_0 - D_1}{T_1} t \tag{4}$$

$$A_{Zt} = \frac{A_{ZT}}{T_1} t. \tag{5}$$

Taking into account the previous expressions, the quadratic function is finally obtained:

$$A_{FLt} = A_{FL0} - \left(\frac{\pi}{2} D_0 \frac{D_0 - D_1}{T_1} + \frac{A_{ZT}}{T_1} \right) t + \frac{\pi}{4} \left(\frac{D_0 - D_1}{T_1} \right)^2 t^2, \tag{6}$$

where

$$A_{FL0} = \frac{\pi}{4} \left(D_0^2 - D_1^2 \right) + A_{ZT} = \text{const}. \tag{7}$$

For the concrete experiment, the tools parameters (Fig. 4 and expression (3)) have the following values:

$$c_M = 50.6 \text{ mm}; r_{MH} = 11 \text{ mm}; r_{MV} = 3 \text{ mm}; a_M = 42.4 \text{ mm}.$$

For the measurements purposes and presentation of the results, it was useful to adopt a liner relationship between the punch travel and time, which does not deviate from reality in conditions of punch constant speed and continuous process course.

The process parameters are the following: the total piece depth $h_{max} = 51$ mm, the total process duration time $T_{max} = 156$ s; time to reach the diameter D_1 amounts to $T_1 = 140$ s.

Based on the tool dimensions, the initial flange area is $A_{FL0} = 5680.9$ mm^2. The specific holder pressure[9] is $q = 2.287$ MPa, so the holding force (the constant value – the R version) is $F_D = qA_{FL0} = 12992.3$ N. Dependence of the flange area on time is obtained as a function: $A_{FLt} = 5680.9 - 51.14t + 0.0755t^2$, mm^2, while the holding force function (according to expression (1)) is:

$$F_D = 12992.3 - 116.95t + 0.1726t^2, \text{ N} \tag{8}$$

Since the function of the holding force, according to expression (8) has a decreasing character, in presentation of results it was denoted by abbreviation DEC for decreasing.

During the experiment, the friction regime at the flange was formed in three ways. Firstly, approximately dry friction, with completely degreased surfaces (triple cleaning with acetone of all the contact surfaces of the tool and the sheet) and metal contact (used notation: D – dry). Secondly, the friction regime with lubrication (denoted as: O – oil) by the mineral oil for deep drawing, with the following characteristics: kinematic viscosity 42 mPa s and density 0.93 g/cm^3. The oil was abundantly applied by the sponge at all the four flange surfaces (Fig. 1). The third type of the friction conditions was realised by the simultaneous application of the mentioned oil and polyethylene (PET) foil (denoted: O+F – oil and foil), by which the contact surfaces are completely separated during the forming process.

RESULTS AND DISCUSSION

In Table 1 are given the basic characteristics of the single-sided galvanised sheet DC04+ZE: the tensile strength (R_M), the yield strength (R_P), extension at fracture (A_{80}), the strain hardening exponent (n) and the coefficient of the normal anisotropy (r).

Table 1. Material properties

DC04+ZE − s_0 = 0.8 mm							
	R_M (MPa)	R_P (MPa)	R_P/R_M	A_{80} (%)	n	r	strengthening curve aproximation
0°	304.4	190.0	0.62	36.1	0.245	1.309	$K = 552.9\varphi^{0.245}$
45°	319.7	205.8	0.644	30.7	0.21	0.98	$K = 538.4\varphi^{0.21}$
90°	303.5	197.5	0.65	34.75	0.22	1.454	$K = 520.8\varphi^{0.22}$
Average	311.8	199.8	0.64	33.1	0.221	1.181	$K = 537.6\varphi^{0.221}$

Values are given with respect to planar anisotropy in the three directions, with respect to the rolling direction (0°, 45° and 90°).

Influence of the contact conditions and the galvanic coating can be observed on the wrinkles and fracture limiting diagrams, Fig. 5*a* for the sheet DC04 without coating and in Fig. 5*b* for the sheet DC04+ZE with the single sided coating. The sheet side with the coating was facing the punch, thus the coating stayed at the inside surface, that is the most frequent case in practice. As previously men-

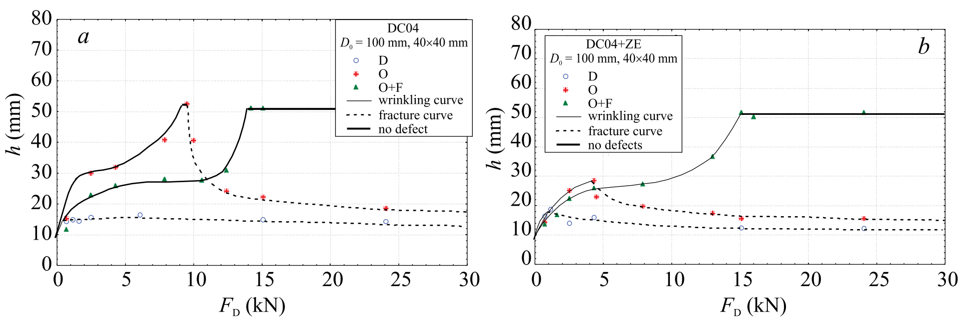

Fig. 5. Wrinkle-fracture limit diagram for uncoated sheet (*a*) and coated sheet (*b*)

tioned, from these diagrams is possible to perform the optimisation of the constant value of force F_D. The criterion is the largest drawing depth. For instance, in Fig. 5*a*, for the friction regime (O), the optimum force is F_D = 9.5 kN. In Fig. 5*b* we have F_D=1.5 kN (D), F_D=4.5 kN (O) and F_D=15 kN (O+F). Besides the analysis of the contact conditions, the limiting diagrams of wrinkles and destruction can be used for optimisation of the constant holding force.

Influence of coating is very prominent at the friction regime (O) at the flange. The unfavourable combination is created of the friction at the flange and the decreased friction towards the punch due to the soft coating which acts as a solid lubricating layer. In that zone more favourable is the increased friction for the more stable process course[1]. The effect is the significant decrease of the maximum drawing depth for the sheet with coating (Fig. 5*b*). In extreme friction regimes (D and O+F) the influence of coating is not the decisive one and results are similar for both materials.

In Fig. 6*a* are shown dependencies of the forming force on the punch travel for the process with constant holding force according to the recommendations (R). The case with application of oil and foil was not performed, since it is obvious that one enters into the wrinkles range. For dry surfaces (D) the realised piece depth was 10.4 mm. When the oil was used (O) the depth was 17.2 mm.

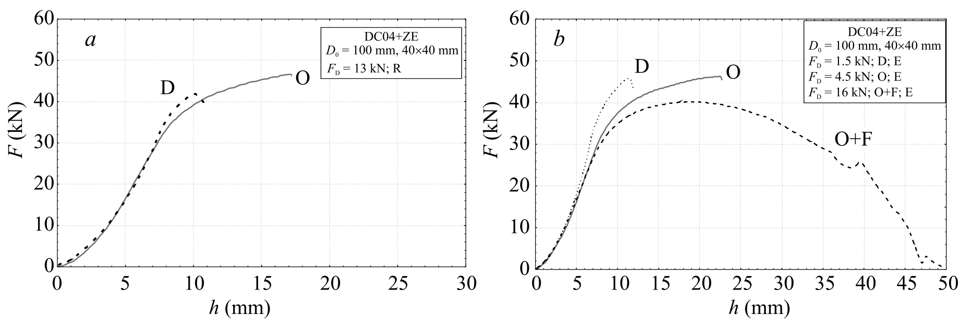

Fig. 6. Forming forces, one-phase process, F_D = const

Figure 6*b* shows the process course for all the three friction regimes and application of the optimised holding force (E). In regime (D) the realised depth was 12.6 mm (increase of 21.2% with respect to Fig. 6*a*). In regime (O) drawing depth is 22.7 mm (increase of 31.9%). In the case when oil and foil were applied a full depth of the piece was obtained, without defects that confirms the positive effects of combining the extremely low friction and sufficiently high intensity of F_D.

In Fig. 7*a* and *b* are shown the appearance of the strain fields of the main surface strains and their relation to the limiting formability curves (FLD). The characteristic loops can be observed, which, for the worse conditions (Fig. 7*a*), are narrowed at the horizontal direction and they enter deeper into the range of the instable deformation between the FLD. Under the more favourable conditions, with

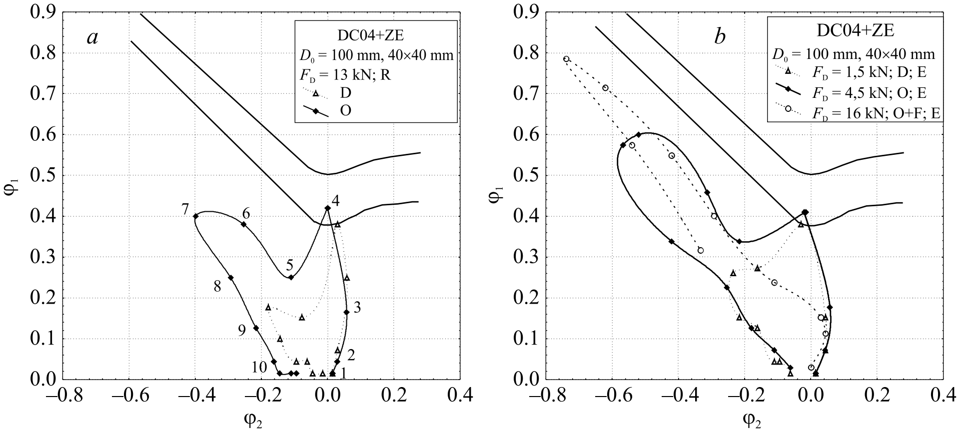

Fig. 7. Strain distributions, one-phase process, F_D = const

the optimised force F_D (E version), the loops are wider, with smaller contact with instable zones of the FLD. The reference form is the loop at the smallest friction (O+F) and successfully conducted forming process (Fig. 7*b*). The strain measurement was done in the optical way in the piece diagonal direction, where the initial position of the circular grid was at the piece bottom center.

In Fig. 8*a* are given dependencies of the forming force and the decreasing holding force (F_D – DEC; R) on the punch travel. It can be seen how the control system of the experimental device realises (in the form of the stairs-like line) the quadratic parabola (expression (8)). A significant effect was noticed of maintaining the constant contact pressure on the holder by means of the decreasing function F_D. For the both friction regimes (D and O) the depth is larger than for application of the constant force F_D (R), (Fig. 6*a*). For the dry surfaces (D) the increase is 31.7% (realised depth of 13.7 mm), for application of oil (O) the increase

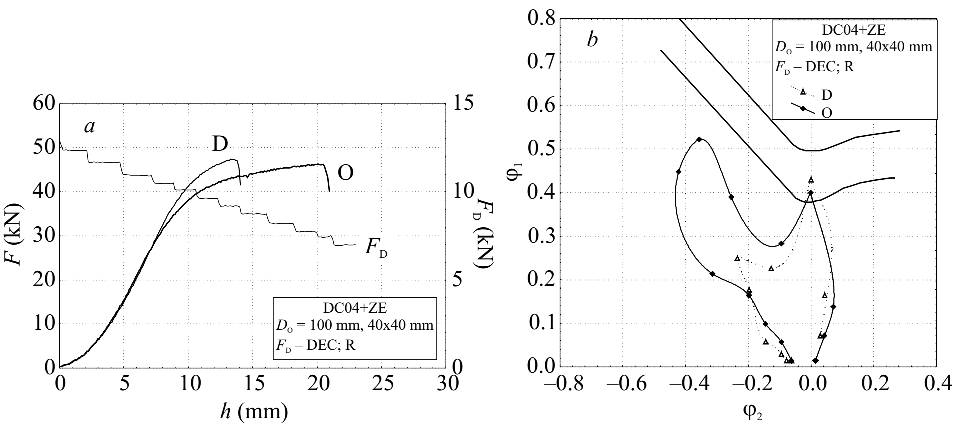

Fig. 8. Forming forces (*a*) and strain distributions (b), one-phase process, $F_D \neq$ const

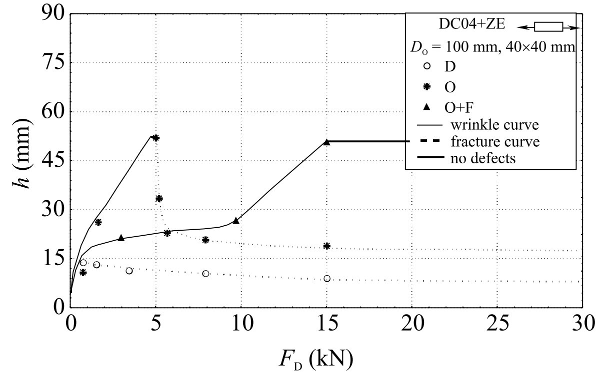

Fig. 9. Wrinkle-fracture limit diagram, two-phase forming

is 19.1% (depth of 20.5 mm). In Fig. 8*b* the improvements are also clearly visible. The distribution of the surface strains is better with respect to that in Fig. 7*a*, especially when lubrication of the flange by oil is applied.

It is known that in drawing the box-like pieces the strains in the lateral sides are significantly smaller. That was the reason that, in the nonmonotonous procedure, the tension direction from the first phase to be set perpendicular to the two lateral sides.

In Fig. 9 is shown the wrinkles and fracture limit diagram for the realised nonmonotonous process. The influence of the nonmonotonousness can be estimated by comparison to Fig. 5*b*. The extreme friction conditions are dominantly influential and they suppress the nonmonotonousness of the process to the second position. In the case of application of oil and foil at the flange, significant changes were not noticed. In dry contact surfaces the prior tension is less manifested through somewhat smaller realised drawing depths. In the friction regime (O) interesting effect occurs. In the very narrow zone of the holding force of about 15 kN, the drawing process continues successfully to the end, without defects.

Thus, only in conditions of applying oil lubrication at the flange, the influence of the first phase of the nonmonotonous process is clearly manifested as improvement of the process performances in the technological sense (obtained full drawing depth of the piece without defects).

In Fig. 10*a* notation T1 next to the material notation points to the fact that uniaxial tension is present in the first phase of the process. The form of the curves is similar to those of Fig. 6*a*; the drawing depth for dry surfaces (D) is similar, but when lubrication by oil (O) is applied the depth of 22.8 mm is achieved that represents an increase of 32.6% with respect to the case in Fig. 6*a*. The appearance of prominent anisotropy direction, formed in the first phase, and its most favourable influence with respect to the piece geometry, only in conditions of the friction on the flange (O), delays the appearance of defects on the piece that can be significant from a technological point of view. The surface strains distributions (Fig. 10*b*)

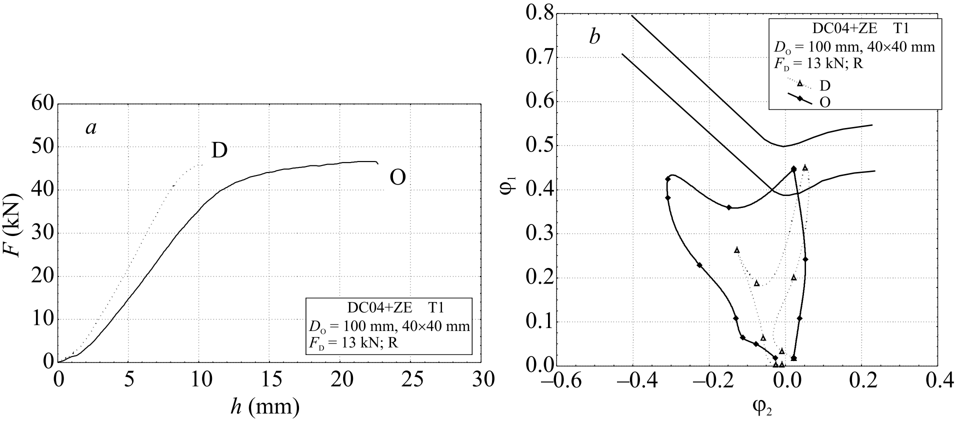

Fig. 10. Forming forces (*a*) and strain distributions (*b*), two-phase process, F_D = const

show that the material plasticity is fully exploited as a consequence of the two-phase nonmonotonous process. The strain intensities are higher with respect to the monotonous procedure.

In accordance with the selected procedure and at the nonmonotonous process, the value for the contact pressure applied is 2.287 MPa and the corresponding dependence of the decreasing holding force (expression (8)). Effects on the process course are visible in Fig. 11*a*. In lubrication by oil, the drawing depth (22.5 mm) increases for 10.5% with respect to Fig. 10*a*, and 22.9% with respect to Fig. 6*a*.

Figure 11*b* (for the case application of oil) shows the increased effect of the strain surface distribution improvement with respect to the monotonous process.

In Fig. 12 is shown the histogram, which illustrates at one place the influence of the friction at the flange (dry surfaces – D and application of oil – O), two ways

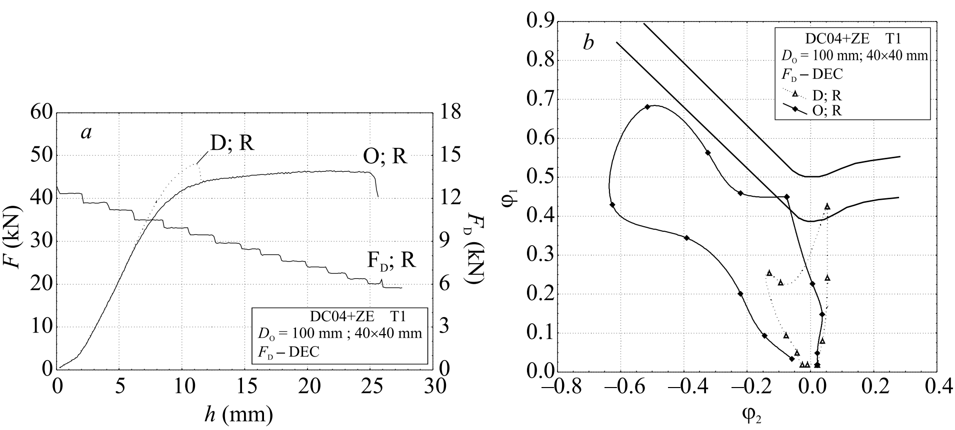

Fig. 11. Forming forces (*a*) and strain distributions (*b*), two-phase process, $F_D \neq$ const

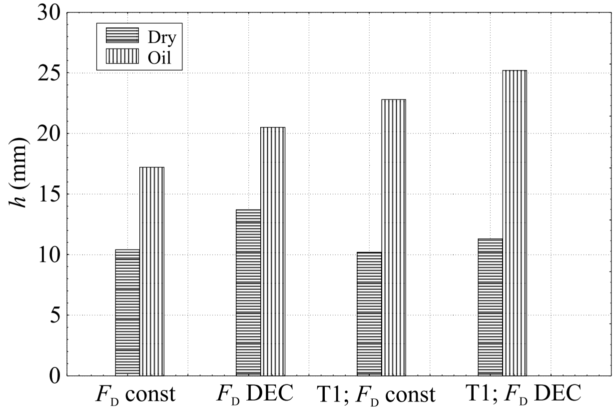

Fig. 12. Review of different influences on drawing depth

of applying the normal force (constant and decreasing – DEC) and two ways of the process course (monotonous and nonmonotonous – T1) on the most significant macroindicator – the drawing depth.

CONCLUSIONS

The holding force at the flange of the box-like pieces, which are being formed by deep drawing from sheets with single side galvanic coating, represents the tribological parameter that can essentially influence the course and results of the deformation process.

Based on the presented results, one concludes that under conditions of lubrication by the adequate oil, the holding force, defined by the constant pressure on the flange criterion, can favourably influence the macroindicators like the drawing depth and also on the distributions of the surface strains, which illustrate the behaviour of individual zones of the piece during the forming process.

Nonmonotonousness of the process, according to the scheme realised in this paper, besides the favourable influence of the constant pressure on the flange, additionally increases the realised positive effects.

Results of this paper show the significant influence of the combined action of tribological conditions (normal force, friction regimes, coatings on material) and nonmonotonousness of the process according to one stress-strain scheme and also point to further investigations of the synergic action of the nonmonotonousness of the forming process and normal force at the flange.

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Received 13 April 2010
Revised 2 July 2010