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VALIDATION OF THE RESULTS OF NUMERICAL SIMULATION OF DEEP DRAWING OF TAILOR WELDED BLANKS

WERYFIKACJA WYNIKÓW NUMERYCZNEJ SYMULACJI PROCESU TŁOCZENIA WSADÓW SPAWANYCH LASEREM TYPU TAILORED BLANKS

The main subject of the paper is the analysis of plastic flow of tailored blanks in deep drawing processes. It has been shown in the present study that the key issue of the discussed problem is the development of a method which would allow to analyse nonuniform flow of blanks characterized by large changes of geometry, strain and stress state in the deformation process. Estimation of the formability of a tailored blank is not possible taking into account only the formability of the component sheets, without considering the shape of the drawn part as well as the location and orientation of the weld line with respect to directions of principal stresses in the blank. The present paper presents a model of tailored blanks which can be used in a finite element simulation to determine the formability of such blanks. The proposed solution makes use of the results obtained in experimental tests on tailored blanks. The relationship between the formability of the base material and the formability of the weld zone has been found. Model parameters can be determined from the characteristics of the component sheets and properties of the welded zone. Numerical simulation was carried out using the developed model. It was found that the flow of a tailored blank depends on the orientation of the weld line with respect to the directions of principal stresses and the formability of a tailored blank depends on the characteristics of the component sheets and the quality of the weld. Theoretical model of a tailored blank and numerical simulation have been validated by experimental tests. Local strains from numerical simulation have been presented on the forming limit diagrams and compared with strains measured in experiments.

Podstawowy problem zawarty w artykule dotyczący analizy plastycznego płynięcia blachy łączonej (tailored blanks) w procesach tłoczenia. Jak wykazano w badaniach, istota zagadnienia dotyczy opracowania metody analizy płynięcia niejednorodnego materiału blachy łączonej w procesach tłoczenia charakteryzujących się zmiennością geometrii oraz zmiennością stanu naprężenia odkształcenia strefy kształtowania. Ponieważ, ocena tłoczności dokonywana na

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podstawie badań blach składowych nie pozwala na prognozowanie przebiegu procesu tłoczenia blachy łączonej, zwłaszcza dla bliżej nie sprecyzowanego kształtu wytłoczki i miejsca położenia oraz orientacji linii spoiny względem kierunków działania sił kształtujących blachę, dlatego w opracowano model materiału blachy łączonej, pozwalający na stosowanie symulacji metodą elementów skończonych, do analizy i projektowania procesów tłoczenia tego rodzaju wsadów. Problem rozwiązano wykorzystując badania numeryczne oraz ruchowe próby tłoczenia blach łączonych spoiną laserową. Istotny element tych badań to określenie związków pomiędzy właściwościami odkształcanego materiału a właściwościami strefy połączenia. Opracowano metodę wyznaczania parametrów modelu, jedynie w oparciu o charakterystyki blach składowych oraz właściwości strefy połączenia. Badania te posłużyły do budowy modelu blachy łączonej pozwalającego na numeryczną symulację procesu tłoczenia blach łączonych. Stwierdzono, że odkształcenie blachy spawanej determinowane jest orientacją linii spawu względem kierunku działania obciążeń, zaś podatność do tłoczenia blach łączonych zależy od charakterystyki blach składowych oraz jakości spoiny. Z tego też względu trudno jest określić tłoczność tego rodzaju wsadu uwzględniając wszystkie możliwe warianty połączeń blach. Przeprowadzone obliczenia numeryczne procesu tłoczenia blachy łączonej spoiną laserową, zweryfikowano w ruchowych próbach tłoczenia. Weryfikacji dokonano porównując odkształcenia lokalne zmierzone na wytłoczkach z obliczonymi numerycznie, na tle granicznych krzywych tłoczenia wyznaczonych dla łączonych blach składowych.

1. Introduction

An increasing number of car body parts is manufactured from tailored blanks (or tailor welded blanks). Tailored blanks for a given stamped part are obtained by laser welding of different sheets. Tailored blanks may integrate sheets of different thickness, material properties or surface coatings [1-3]. The process of drawing the blanks with geometrical and physical nonuniformity requires thorough knowledge of formability of component sheets as well as formability of a welded zone. Large number of possible sheet connections and different orientation of weld line in a stamped part makes it impossible to determine the formability of a tailored blank, without considering the stamping process. The problem of formability of tailored blanks in the design process can be looked into by examining the relationship between formability of base material and the formability of the weld zone, with material flow of the tailored blank being determined by numerical simulation [4]. Stress and strain distribution obtained as a result of numerical simulation depends on the theoretical model and its parameters. Sheet model and material properties of the base materials are essential in the analysis of deep drawing process. The flow of a tailored blank is different than the flow of a uniform blank [5-7], due to the difference in thickness and mechanical properties of component sheets as well as the influence of a weld. A theoretical model of tailored blanks should combine material models of the base materials and the weld zone. Theoretical model and simulation of deep drawing of tailored blanks should be validated by comparing to the results of laboratory and industrial examples.

2. Material model of the welded zone

In the studies on the model of tailor welded blanks [5, 6], residual thermal stresses in the tailored blanks after welding were determined by numerical simulation prior to analysis of a deep drawing process. Although this approach provides correct and important results, it still requires simulation of the welding process before simulation of the deep drawing. This would increase analysis time and would limit the practical use of numerical simulation. Approximate results of deep drawing of tailored blanks can be obtained using a simple model in which two base sheets are joined, assuming perfect bonding between them and ignoring the weld (Fig. 1). In this model different material properties are assigned to the zones of different blank components. Mechanical properties of base materials can be described in the standard way by the following hardening law:

$$\sigma_p = C(\varepsilon_0 + \varepsilon)^n, \tag{1}$$

where: σ_p – yield stress, ε – logarithmic strain, ε_0 – initial strain, n – hardening law exponent, C – material constant.

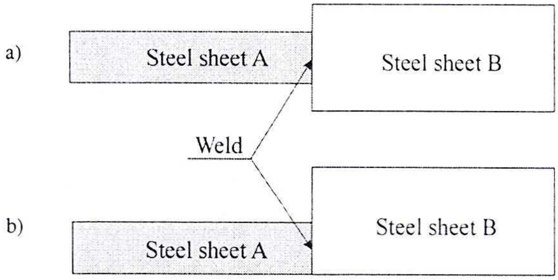

Fig. 1. Simple model of tailored blank

This model is characterised with an abrupt change of properties along the connection line and zero width of the weld zone. Therefore, simulation of deep drawing of tailor welded blanks using this model does not allow to analyse the stress and strain state in the weld zone and its neighbourhood. Fig. 2 presents simulation results of deep drawing of a cylindrical cup. Calculations have been carried out using the geometrical model shown in fig. 1b, for component sheets 1.0 mm and 1.5 mm thick. The examinations have been carried out for DC04 and DX54D+Z type of steel. Both models of tailoring the blanks used in simulation calculations presented in fig.1 show that the differences in characteristics of a material flow in the zone of weld are not significant for practical application. Therefore a geometrical model of blank tailoring has only been used for further calculations (Fig. 1b). Basic standard requirements for technological properties and chemical composition are in accordance with generally accepted standards, i.e., for CD04 steel – Cold-rolled carbon steel flat products for cold forming – Technical delivery conditions European Standard EN 10130:1991/A1:1998; and for DX54D+Z steel – Continuously hot-dip zinc coated low carbon steels strip and sheet

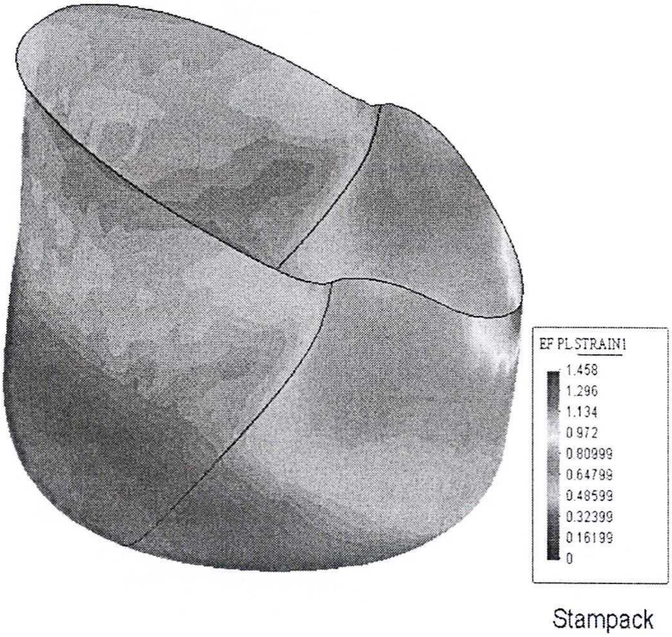

Fig. 2. Simulated distribution of local strain intensity for a cup presented in fig. 3. Tailored blanks 1.0 mm and 1.5 mm thick made of DC04 and DX54D+Z steel

for cold forming – Technical delivery conditions European Standard EN 10142:2000. Mechanical properties of the used sheets , together with hardening law parameters defined by Eq. (1), are presented in tables 1 and 2. Simplified model does not reproduce a restraining action of the weld along its length nor the local deformation changes in the vicinity of the t01, 02 weld line which are observed in practice. Strains along the weld line change discontinuously according to the jump in stress distribution corresponding to discontinuous change of sheet thickness. Measurements of local strains in a real drawpiece, obtained under the same conditions as those used in the numerical simulation (Fig. 3) have shown that unless the weld is stretched along its line, it does not deform or deforms only slightly. Deformations of the weld along its line are equal to deformations of the base material close to the weld line in the direction parallel to the weld line. Deformations in the direction perpendicular to the weld line depend on the strength and plastic properties of the joint sheet components. In consequence, joined sheets close to the weld line undergo deformations in the plane strain or close to the plane strain state.

Basing on these observations, a concept of a three-zone model of tailor welded blank (Fig. 1) has been elaborated [8]. In this model, component sheets *A* and *B* are separated by a zone representing the weld, with the width equal to the average thickness of the joined sheets. Further investigations [8] of the multi-zone model have proved that not only the number of zones, but also their width is important for the accuracy of numerical simulation. The width of the weld zone depends on the parameters of welding process, geometry of the

TABLE 1

DC04 blank properties. Blank thickness – 1.0 mm

UTS [MPa]	PS [MPa]	A_{80} [%]	n	r	IE_{20} [mm]
295	205	39.7	0.181	1.86	10.3
Parameters of hardening law function					
$\sigma_p = 524(\varepsilon + 0.022)^{0.219}$ [MPa]					

Values at 90° to the rolling, on bare sheet.
UTS – ultimate tensile strenght,
PS – proof stress, for 0.2% elongation,
A_{80} – ultimate elongation for measrement base of 80 mm,
r – plastic strein ratio,
IE_{20} – Erichsen test forr ball-shaped punch of 20 mm.

TABLE 2

DX54D+Z blank properties. Blank thickness – 1.5 mm

UTS [MPa]	PS [MPa]	A_{80} [%]	n	r	IE_{20} [mm]
305	215	39.1	0.181	1.83	11.8
Parameters of hardening law function					
$\sigma_p = 519(\varepsilon + 0.022)^{0.206}$ [MPa]					

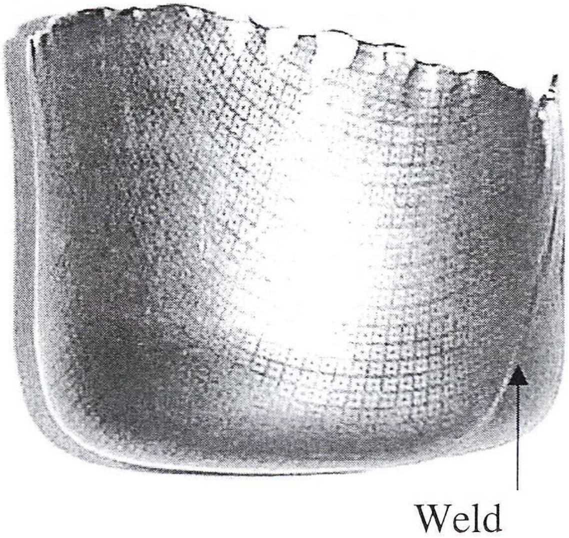

Fig. 3. Photograph of a cup made of tailored blank – component sheets are 1.0 mm and 1.5 mm thick and are made of DC04 and DX54D+Z steel respectively

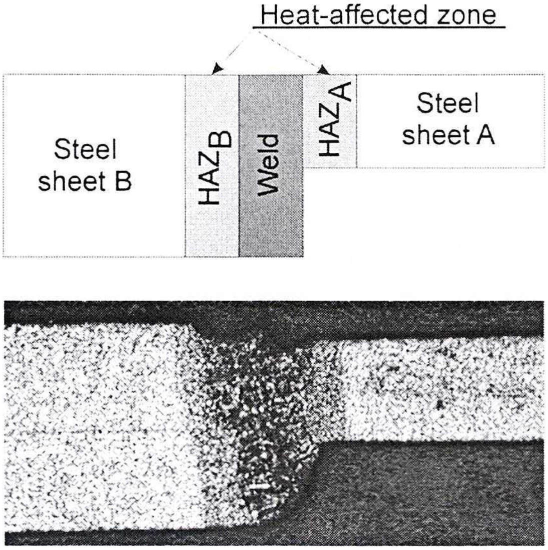

Fig. 4. a) Five-zone model of tailored blank (heat affected zone-HAZ); b) microphotograph of a weld zone

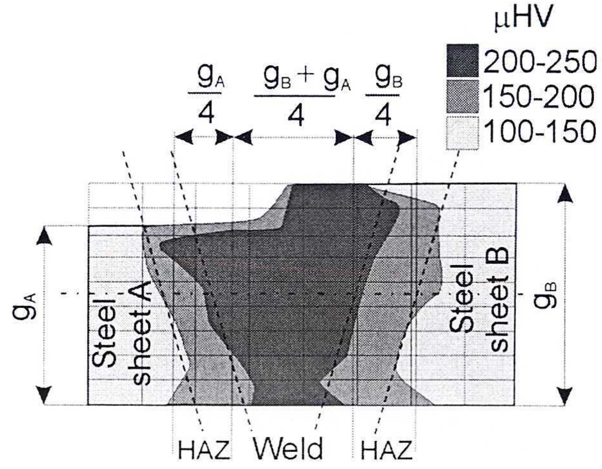

Fig. 5. Distribution of microhardness at a lateral section of blank weld for blanks 1.2 mm and 1.5 mm thick made of H260YD+Z and DX54D+Z steel

connection and the type of the material. Micro-hardness measurements of the welded zone have shown that it is desirable to distinguish in the weld zone three sub-zones: weld bead, which has the highest hardness, and two heat affected zones. Thus, a five-zone model of tailor welded blank has been worked out as shown in Fig. 4. Application of this model requires determining the hardening law parameters for the assumed zones. Since it is difficult to separate weld bead and heat affected zones and performing tensile tests for the material of welded zone is practically impossible, hardening law parameters for the three assumed zones are determined indirectly by means of micro-hardness (μHV) measurements in the welded zone. Modelling of the weld zone has been presented in more detailed way in [7, 8], determination of the geometry of the zones of the weld has been presented in [7, 8] and determination of their physical properties (Fig. 5) has been presented in [8].

3. The example of deep drawing of tailor welded blanks

The following research plan has been adopted for practical validation of the results of numerical simulation of deep drawing of tailor welded blanks:

- experimental study of a deep drawing process, including selection of a part to study, tests of deep drawing of the chosen part, experimental study of forming properties of the material, and analysis of material flow in the drawn part of the tailor welded blank;
- numerical study of a deep drawing process, comprising the following tasks: preparation of finite element model, determination of material and technological data, simulation of a deep drawing process, and validation of calculation results by comparing them to experimental results.

The main objective of the experimental study was to determine the deformation state (by local strain measurements), and to analyse the material flow. Keeping this in mind, a drawing process with unconstrained flow of the blank was chosen. Different states of deformation were expected in the process where the blank was not constrained by either blankholder, or drawbeads. The other aspects of choosing a drawpiece had to consider certain limitations of the particular examination conditions:

- the possibility of performing tests in conditions close to the actual production process, the use of a production press, and the study of different tool and press set-ups and different process parameters;
- the available size of blank, the possibility of blank trimming without special cutting tools, and the possibility of stamping of blanks of different thickness and different properties, joined by laser welding.

The above mentioned criteria are fulfilled by the drawpiece which is shown together with the tools and the size of material in Fig. 6. The drawing tests [9] were carried out for tailored blanks obtained by joining the component blanks made of DX54D+Z steel and H260YD+Z steel. Basic requirements and chemical composition for H260YD+Z steel can be found in Continuously hot-dip coated strip and sheet of steels with higher yield strength for cold forming – Technical delivery conditions European Standard EN 10292:2000.

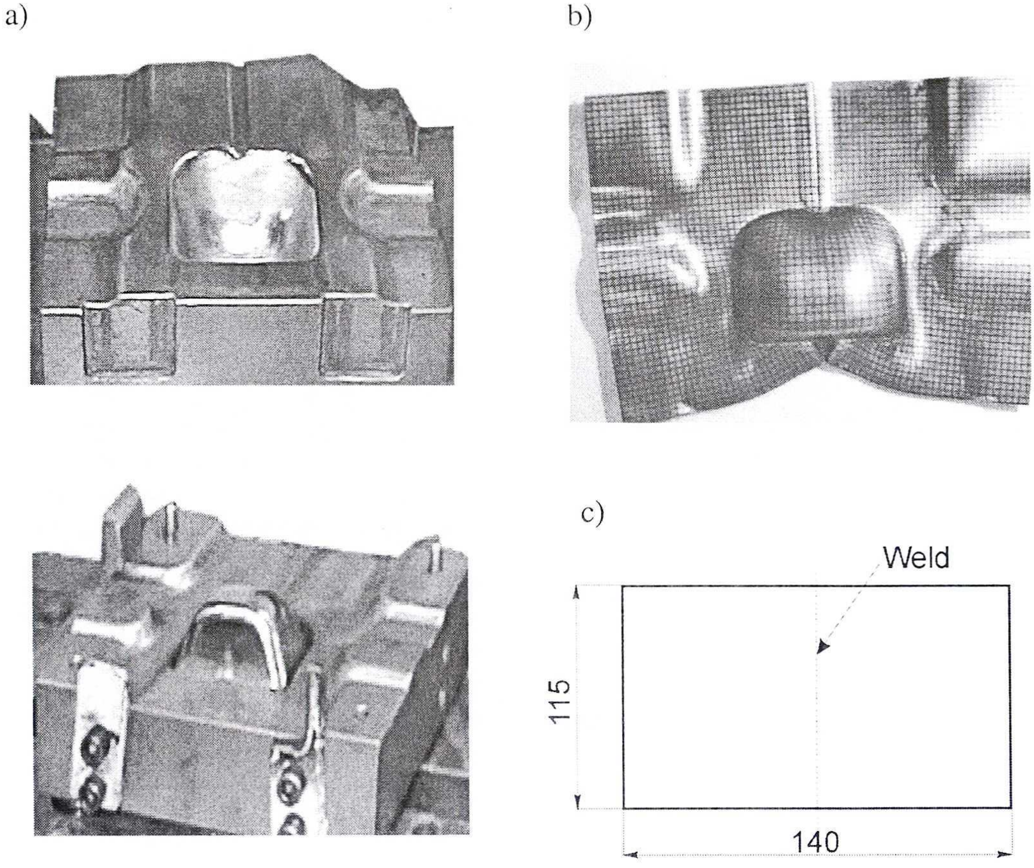

Fig. 6. Photograph: a) set of tools – upper and bottom die block; b) drawpieces made of blank 1.0 mm thick – CD04 type of steel, c) drsawiece made of tailored blank

Hardening law parameters for the blank made of H260YD+Z steel are given in table 3, and for the blank made of DX54D+Z steel in table 2. All the material parameters for the five-zone model of the tailor welded blank for different component sheet combinations (denoted A-A, B-B, A-B) are given in table 4. Stamping tests were carried out using the tools shown in Fig. 6 and the tailor welded blanks with a weld line lying along the shorter axis of symmetry. The drawpieces obtained for different combinations of component sheets are shown in Fig. 7. Figure 8 shows the forming limit diagrams of the studied parts, with local principal strains measured in the area close to the cracking. The drawpieces were made of tailored blanks for various types of joining of the component blanks .Ten drawpieces were made for each type of joining of tailored blanks and local strain was determined in three zones of cracking of the blank applying the method of coordinating net measurements. The results of local deformations were then plotted onto the diagram of forming limit curves (Fig. 8) marking the results obtained for drawpieces of a given type of blank tailoring.

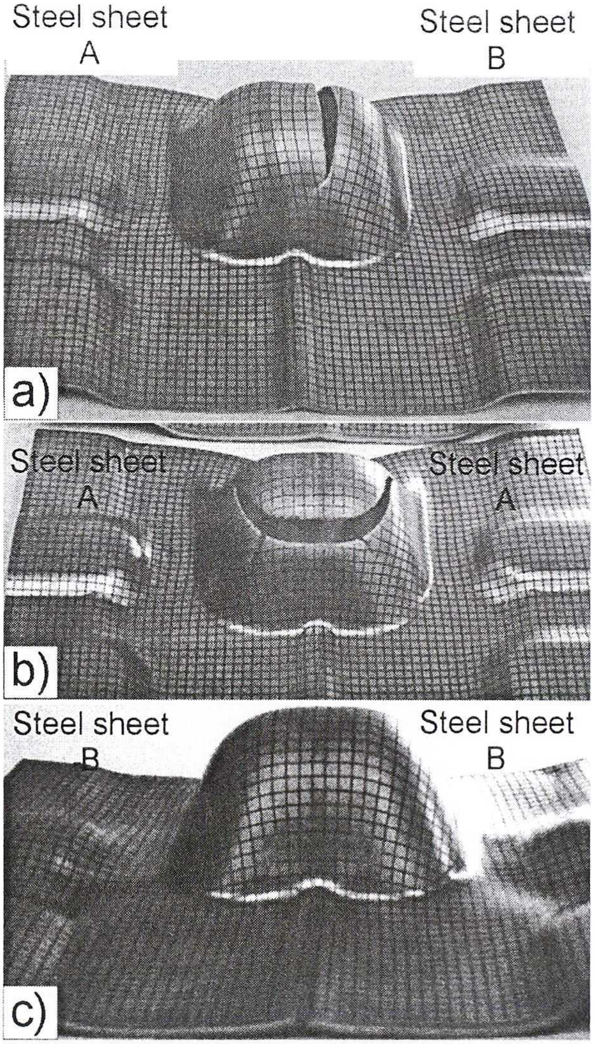

Fig. 7. Photographs of drawieces made of tailored blank for different types of tailoring of A and B blanks. Tailored blank: a) A-B; b) A-A; c) B-B. Denotation of blanks as in table 4

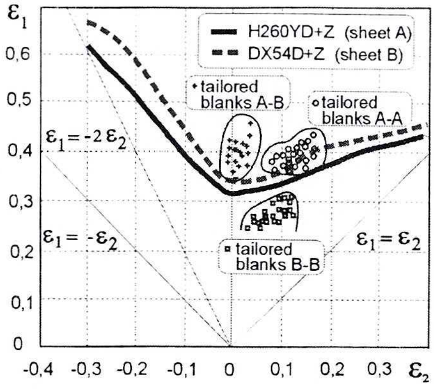

Fig. 8. Local strains in critical zones of the examined drawpieces as compared to limit curves of drawing for the tested blanks

TABLE 3

H260YD+Z blank properties. Blank thickness – 1.2 mm

UTS [MPa]	PS [MPa]	A_{80} [%]	n	r	IE_{20} [mm]
410	315	34.1	0.179	1.562	10.3
Parameters of hardening law function					
$\sigma_p = 598(\varepsilon + 0.038)^{0.224}$ [MPa]					

TABLE 4

Parameters of hardening law for five-zone model of tailored blank with different types of blank tailoring for H260YD+Z and DX54D+Z blanks

Type of tailoring	Thickness/width [mm]			Parameters of hardening law function σ_p [MPa]					
	Sheet	Heat affected zone	Weld bead	Heat affected zone			Weld bead		
				C	ε_0	n	C	ε_0	n
A-B	1.2	0.3	0.70	792	0.041	0.306	896	0.052	0.351
	1.5	0.4		723	0.043	0.306			
A-A	1.2	0.3	0.60	787	0.043	0.302	818	0.045	0.308
B-B	1.5	0.4	0.75	702	0.025	0.298	826	0.027	0.346

A – H260YD+Z blank
B – DX54D+Z blank

4. Simulation of the deep drawing process

The aim of numerical simulations was to verify the accuracy of material flow prediction for the tailor welded blanks with special attention paid to the welded zone. Numerical computations were carried out using the five-zone model. The area of cracking and its form predicted in the simulation were compared to those observed in the experimental studies.

The materials of weld and blank in the heat affected zone are characterized by smaller deformability than the base blank material, due to hardening. Therefore, the flow of a tailor welded blank is different than the flow of a uniform blank, even in the case when the tailor welded blank has been obtained by joining two components of the same material as the compared uniform blank. The drawpiece obtained from the tailored blank features smaller deformability along the weld line, which results in better flow of the blank in the area of joining of the blanks (Fig. 6b).

Formability of tailored blanks depends on the orientation of the weld line with respect to the directions of principal stresses appearing during the drawing process. In the studied process, the flow of material along the weld line at one side of the flange is not restrained, therefore the stress state in the material close to the weld line is characterised by tension in the direction perpendicular to the weld line. This leads to necking of the thinner blank (Fig. 7a). If there is a big difference in strength of the tailored blanks (due to the big difference in thickness, or due to the big difference in mechanical properties), strain localisation and subsequent fracture occurs close to the weld, while in the case of smaller difference in component sheet strength, strain localisation and cracking occurs at a certain distance from the weld. In the analysed case, the difference in strength due to the difference in thickness is compensated by better mechanical properties of the thinner blank (H260D+Z steel, 1.2 mm thick). In tailored blanks denoted *A-A*, there are no evident effects of weld displacement and low drawability of that type of blanks causes cracking during the process of drawing. The crack is initiated in the weld and is typical for the process of bulging.

The material flow of the examined blanks during the process of drawing can be analysed applying forming limit diagrams. The local deformations have been simulated by the method of finite elements and Fig. 9-11 present these deformations on drawpieces made of tailored blanks at the final stage of the drawing process for different types of tailoring of *A* and *B* blanks. In the case of tailored blanks denoted *A-A* (H260D+Z) (Fig. 9) and tailoring of *A-B* type (Fig. 11) cracking can occur. In the case of tailored blanks denoted *B-B* (DX54D+Z) (Fig. 10) it is unlikely that the cracking of the blank will occur, although the points which characterize the state of strain (minimum and maximum principal strains, 1 and 2 respectively on the mid-surface of the sheet) are close to the forming limit curve. This is in agreement with the experimental results (Fig. 6). The areas of possible cracking for the examined combinations of component sheets are shown in Fig. 12. This figure presents the formed shape of drawpieces where elements have been eliminated in those areas where the state of strain corresponds to the points which are above the curve of limit strains. These areas are different for different combinations of tailored blanks and they are regarded as critical zones which can be determined by the method of simulation since cracks are most likely to occur there.

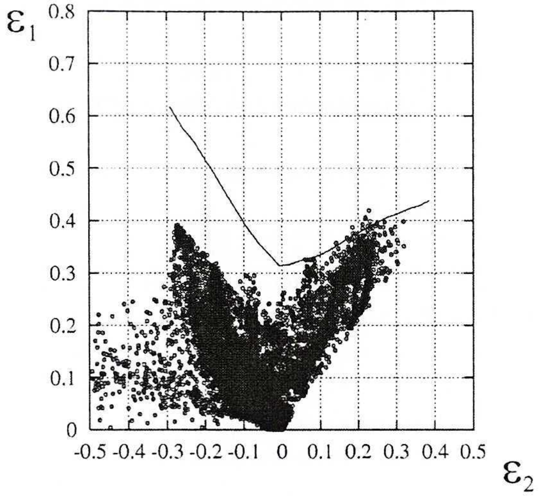

Fig. 9. Diagram of limit strains for a drawpiece made of tailored blank of *A-A* (H260YD+Z) type

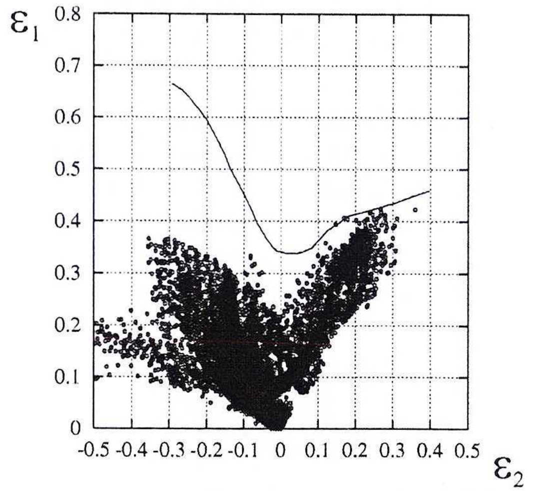

Fig. 10. Diagram of limit strains for a drawpiece made of tailored blank of *B-B* (DX54D+Z) type

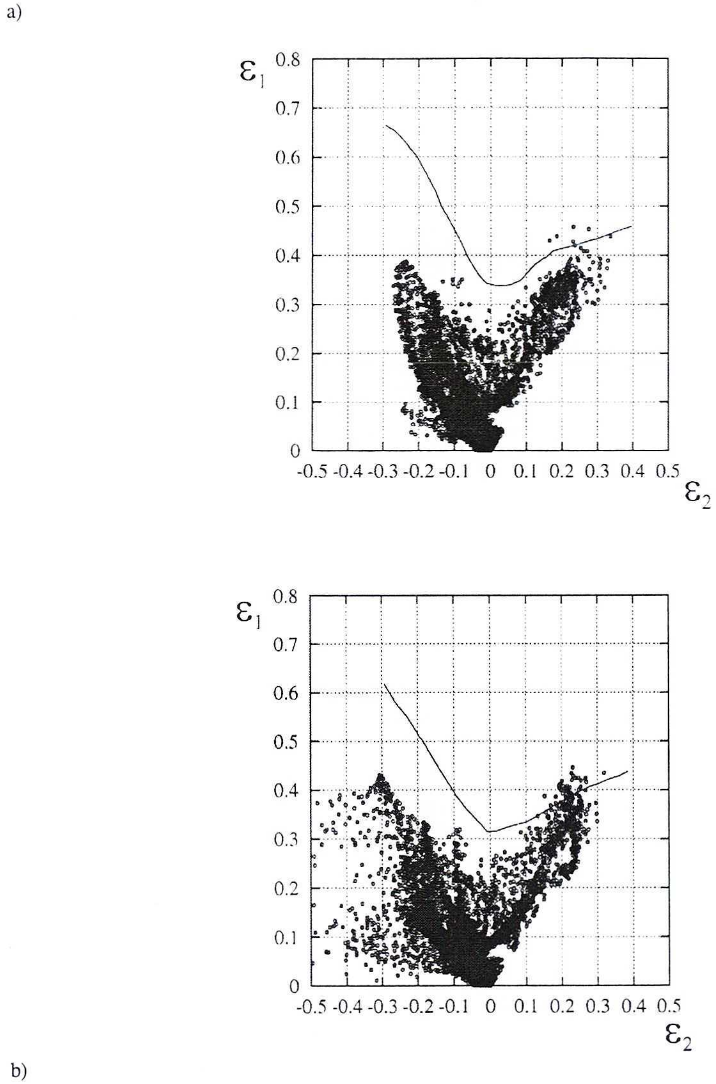

Fig. 11. Diagram of limit strains for a drawpiece made of tailored blank of *A-B* type; a) zone of DX54D+Z blank, b) zone of H260YD+Z blank

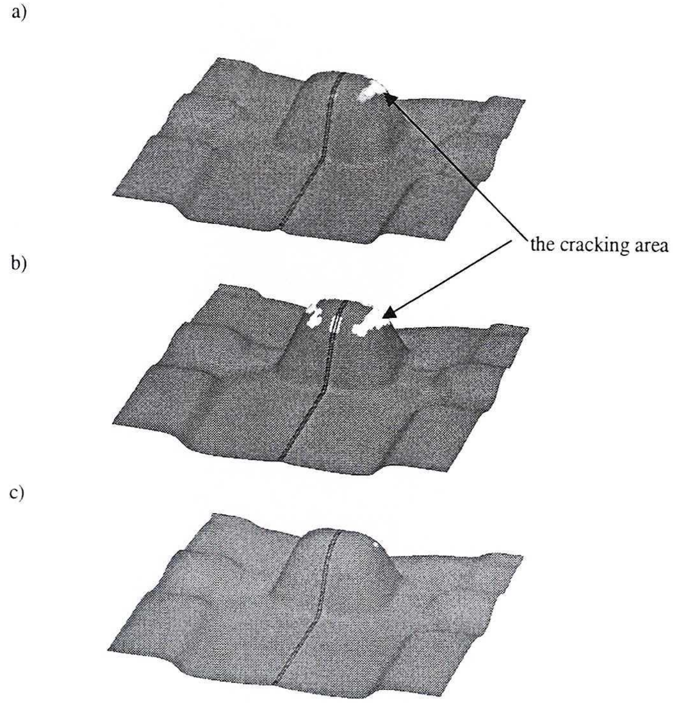

Fig. 12. Final shapes of drawpieces made of tailored blanks for different types of blank tailoring – the actual zones of cracks have been marked; a) *A-B*; b) *A-A*; c) *B-B*. Denotation of blanks as in table 4

5. Conclusions

Drawability of tailored blanks depends largely on the characteristics of component blanks and the quality of the weld. Therefore it is difficult to determine the drawability of that kind of material taking into account all the possible types of blank tailoring. In general, this problem concerns elaborating the method of analysing the flow of nonuniform material of tailored blank in the drawing processes which feature variability of geometry, stress and strain in the area of forming. This is particularly difficult if the characteristics of component blanks are the only criteria. The mode of blank flow in the weld zone and in the neighbouring zones is of a nonuniform nature which appears to be the main problem in designing the drawing process. This is due to diversification of strength of the tailored blanks and hardening of the weld. The nonuniform mode of blank flow may result in the local change of strain scheme and in the change of the position of critical areas of a drawpiece, i.e. the potential areas of the loss of strain stability which in turn can result in cracking of the blank. These changes are difficult to predict and therefore the suggested solution to that problem is the application of computer simulation techniques in the designed process.

Evaluation of the obtained results has revealed that the five-zone model makes it possible to describe with great precision the characteristics of laser welded blanks and it also enables to simulate the drawing process precisely enough for industrial application. The simplified three-zone model can be used for the simulation of the process of drawing of tailored blanks in such cases where the precise local strain distribution in the neighbouring zones of the weld core (which are the zones of heat effect) is not of great significance. The suggested model of tailored blanks allows to determine the parameters of the model, taking into account the orientation of the direction of component blanks rolling in relation to the direction of weld line. This allows to consider the anisotropic characteristics of tailored blanks in calculations which simulate the drawing process.

Using the elaborated model of tailored blank material – both three-zone model and five-zone model – it is possible to analyse the process of nonuniform flow of material for various types of blank tailoring and different orientation of the weld as well as for the successive types of dies. Furthermore, the application finite elements method in any simulation programme enables to analyse elasticity-plasticity aspects of nonuniform flow of material. Set of information obtained in the course of simulation calculations allows to take the right decisions for making any changes in the design of the material and drawing technology.

REFERENCES

[1] H. Kusuda, T. Toshiyoku, N. Fumiaki, J. of Materials Processing Technology **1,** 134 (1997).
[2] B. Kinsey, L. Zhihong, C. Jian, J. of Materials Processing Technology **1,** 145 (2000).
[3] K. Lange, J. of Materials Processing Technology **1,** 1 (1997).
[4] K. M. Zhao, B. K. Chun, J. K. Lee, J. of Materials Processing Technology **2,** 117 (2001).
[5] A. Piela, Rudy i Metale Nieżelazne **11,** 527 (2001).
[6] Z. Zimniak, A. Piela, J. of Materials Processing Technology **1-3,** 254 (2000).
[7] A. Piela, A. Kocańda, NUMIFORM 2001, ed., K. Mori, Toyohashi, Japan, 795 (2001).
[8] A. Piela, M. Hyrcza, J. Lisok, Przegląd Mechaniczny **4,** 19 (2001).
[9] J. Rojek, A. Piela, Informatyka w technologii metali, eds., J. Kusiak, M. Pietrzyk, F. Grosman, A. Piela, Informatyka w Technologii Metali, 198 (2002).

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