IDENTIFICATION OF THE FLOW STRESS MODEL FOR THE STRIP MATERIAL SUBJECT TO BULK DEFORMATION[*]

MATEUSZ AMBROZIŃSKI[1]*, ROMAN KUZIAK[2]

[1]*AGH University of Science and Technology, al. Mickiewicza 30, 30-059 Krakow, Poland*
[2]*Institute for Ferrous Metallurgy, Gliwice, Poland*
*Corresponding author: mambroz@agh.edu.pl

Abstract

The problem of determination of the flow stress of sheet material for larger strains was investigated. Plastometric tests for the sample made as a pile of disks cut from the strip were performed. In order to avoid sliding the discs were placed in a tube made of the IF steel and CuCr alloy. Flow stress of the IF steel and CuCr alloy was determined on the basis of compression tests for cylindrical samples. With the data obtained it was possible to perform the analysis to identify the model for TRIP steel using inverse analysis for the compression of the assembled samples. The developed model was used in two case studies. The first was simulation of stamping of the automotive part. The second was simulation of strength of the anchor-concrete joint, in which the expansion sleeve was made of the TRIP steel.

Key words: sheet metal, compression tests, inverse analysis

1. INTRODUCTION

The problem of identification of flow stress model for metallic materials is well studied in the scientific literature. In bulk forming processes plastometric compression tests are used and inverse analysis is applied for an accurate interpretation of the results. The authors' algorithm for the inverse solution was described by Szeliga et al. (2006). Flow stress model for sheet forming is usually built on the basis of tensile tests. More advanced experimental techniques like bi-axial tension test are recently used, see for example (Vegter & van den Boogaard, 2006). Apart from the flow stress, these tests generate information regarding the anisotropy and allow to formulate the flow rule (Banabic, 2010). Small strains that can be applied to the samples are the main limitation of these tests. Beyond this, present

work was done for the TRIP steels. TRIP steel microstructure is obtained in the continuous annealing process after cold rolling, when the thickness of the strip is small. It is not possible to cut from the strip standard cylindrical samples for compression on the Gleeble simulator.

Intensive search for experimental methods, which allow to determine mechanical properties of strip material to larger strains, has been recently observed. Such a need results from both:
– the specific character of sheet forming in which local strains can exceed those achieved in tensile tests,
– extensively developing metal forming methods of bulk-sheet forming (Schneider & Merklein, 2011; Merklein et al., 2012; Merklein et al., 2013).

The objectives of the present work were formulated with the above remarks in mind. To obtain larger strains compression tests of a pile of discs made of the investigated strip were performed. To

---

avoid slipping of discs the pile was put in a tube made of a material with known flow stress. Inverse analysis was applied for interpretation of the results accounting for the influence of the external tube material. The developed flow stress model was applied to simulations of the stamping process of an automotive part and deformation of the expansion of a sleeve used to connect an anchor with a concrete plate.

2. EXPERIMENT

2.1. Material and test conditions

Compression tests for a pile of roundels cut from the strip were performed. Since roundels during compression were sliding against each other, the pile was put in a tubes made both of the IF steel and CuCr alloy (Fig. **1**). Two kinds of the tube material with various flow stress were used to determine the extent to which the results can be affected. Compression of bulky cylindrical samples made of IF steel and CuCr alloy was performed first to determine the flow stress model for these materials in the temperature range 20-200°C and the strain rate in the range 0.001 – 1 s^{-1}. Following this, piles of disks in IF steel tube were compressed to the total strain of 1 with the same deformation conditions.
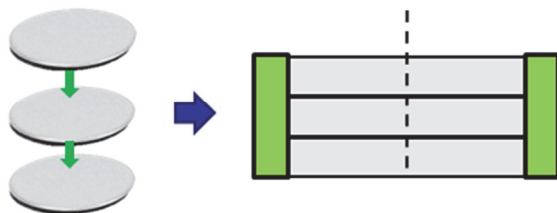

Fig. 1. *Schematic illustration of the sample collected of TRIP steel disks in the sleeve made of the IF steel or CuCr alloy.*

The tested material was TRIP steel strip containing 0.22%C, 1.50%Mn, 0.09%Si, 0.014%P, 0.005%S, 0.03%Cr, 0.02%Ni, 0.01%Mo, 0.004%Ti, 1.7%Al. IF steel used for the sleeve, which prevents disks sliding, contained 0.003%C, 0.15%Mn, 0.023%Si, 0.017%P, 0.012%S, >0.028%Ti, 0.003%N. CuCr alloy contained 0.81%Cr, 0.026%Fe and balance Cu. Thickness of the TRIP steel strip was 1.45 mm. Solid samples dimension was ϕ8×4.35 mm for the IF steel and ϕ7×4.35 mm for the CuCr alloy. Disks with ϕ7×1.45 mm were cut from the TRIP steel strip and put into IF steel or CuCr tube with ϕ8×ϕ7×4.35 mm. These samples were compressed on the Gleeble 3800 simulator at
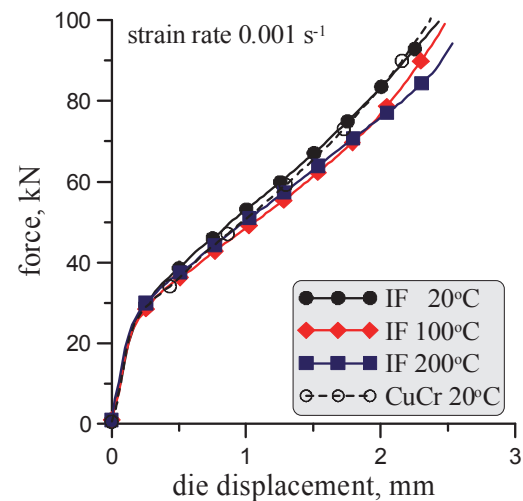
temperatures of 20°C, 100°C and 200°C and at strain rates of 0.001 s^{-1}, 0.1 s^{-1} and 1 s^{-1}.

2.2. Results

The selected results of force measurements in the compression tests for the assembled samples are shown in Fig. **2**. The results analysis shows that the difference between loads obtained for IF steel and CuCu sleeve is very small.
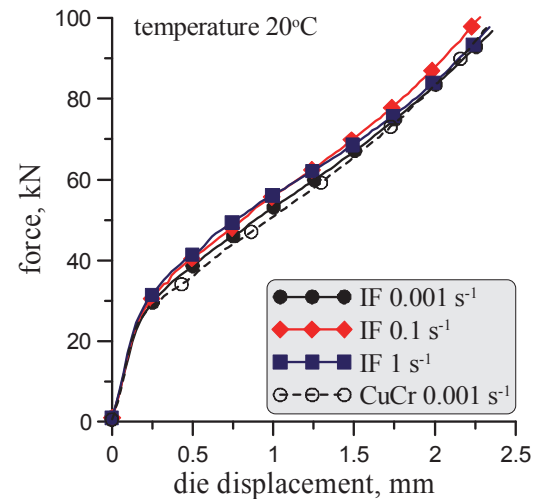
Fig. 2. *Selected results of measurements of compression force for the pile of TRIP steel in IF steel tube and CuCr alloy tube, temperature 20°C (a) and strain rate 0.001 (b).*

For all tests the temperature was measured with thermocouple spot welded to the side of the sample. The results of the temperature measurements are shown in Fig. **3**. Analysis of the measured temperatures shows that in case of tests with low strain rate the control system was capable of compensating heat generation due to plastic work and friction, as well

as the heat transfer to the surrounding, and reasonably stable temperature was maintained. In fast tests (1 s⁻¹) the temperature increase was observed. To compensate the influence of the temperature variations, the inverse analysis was applied. In case of the direct problem model the measured temperatures in the inverse analysis were used as Dirichlet boundary condition.
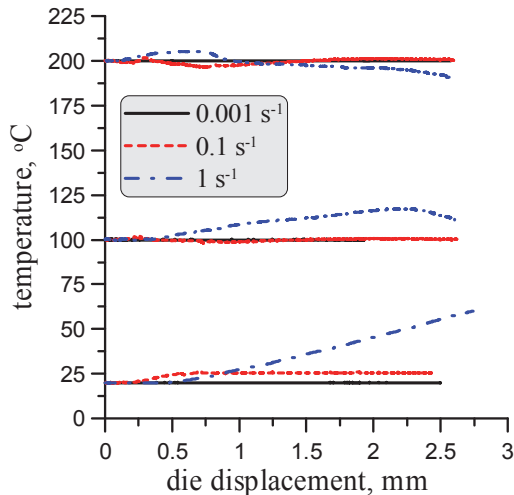

Fig. 3. *Results of the temperature measurements during compression tests.*

3. IDENTIFICATION OF THE FLOW STRESS MODEL

3.1. Inverse algorithm

Interpretation of the results of compression tests was based on the inverse analysis capable of eliminating, or at least minimizing the influence of such disturbances as inhomogeneity of strains, stresses and temperatures, see (Gavrus et al., 1996; Gelin & Ghouati, 1994, Szeliga et al., 2006) and allows flow stress to be determined independently of the method of testing. Capabilities of the inverse analysis to improve interpretation of the results of plastometric tests were confirmed by Gawąd et al. (2005). The two-step algorithm described in details by Szeliga et al. (2006) was used in the present work. The quadratic norm of the error between measured and calculated compression loads was used as the objective function:

$$\Phi = \sqrt{\frac{1}{Nt} \sum_{i=1}^{Nt} \left[\frac{1}{Ns} \sum_{j=1}^{Ns} \left(\frac{F_{ij}^m - F_{ij}^c}{F_{ij}^m} \right)^2 \right]} \qquad (1)$$

where: *Nt* – number of tests, *Ns* – number of load measurement sampling points in one test, F^m, F^c, - measured and calculated load, respectively.

Direct problem model is used to calculate F_c in the objective function (1). This model is based on the FE thermal mechanical solution for metal forming problems. Details of this solution are given by Pietrzyk (2000) and are not repeated here. Friction coefficient of 0.04, determined earlier for the cold compression tests performed on Gleeble 3800, was used in the present work.

In the present work the inverse analysis had an additional task, which was to account for the influence of the IF steel and CuCr alloy sleeve. Therefore, inverse analysis for the compression test of the solid IF steel and CuCr alloy cylindrical samples was performed in the first place and the flow stress model for this material was determined. This model was implemented in the FE code, which was used to simulate compression of the sample assembled of TRIP steel roundels and IF steel or CuCr alloy sleeve.

3.2. Inverse analysis for the IF and CuCr samples

The selected results of the inverse analysis for the IF steel and CuCr alloy are shown in figure 4. These curves represent flow stress as a function of strain and they can be considered a property of the material for isothermal, constant strain rate conditions. The functions introduced in the finite element program in the tabular form will give perfect agreement between measured and predicted loads.

The flow stress in the finite element simulations has to be described in a wide range of temperatures and strain rates. Therefore, the description of this relation in the form of algebraic or differential equations is needed. Thus, the next step of the inverse analysis involved determination of the coefficients of the function describing the flow stress. The behaviour of polycrystals during plastic deformation depends on many factors, the influence of which should be accounted for, which is difficult. To overcome this problem polycrystals are described by flow (stress-strain) curve, which represents statistically all mentioned phenomena. Large number of flow stress models for metal forming were published in the scientific literature in the last two decades.
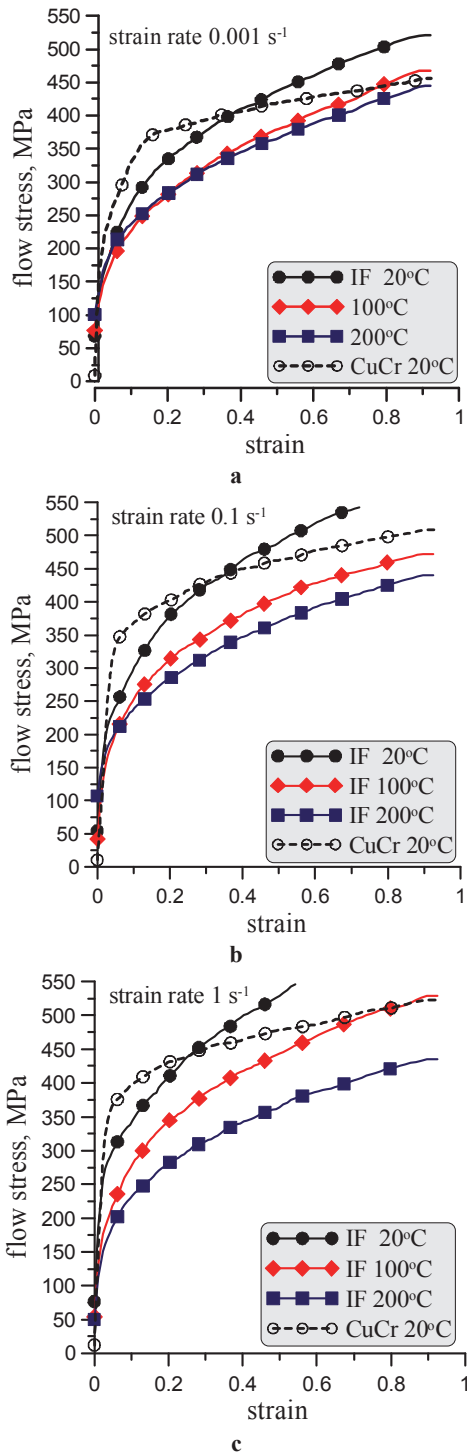
Fig. 4. *Flow stress vs. strain in the tabular form determined in the first step of the inverse analysis for the IF steel and the CuCr alloy for the strain rate of 0.001 s⁻¹ (a), 0.1 s⁻¹ (b) and 1 s⁻¹ (c).*

These models are characterised by various complexity of mathematical formulation and various predictive capabilities. There were several attempts to classify these models, see for example (Grosman, 1997; Schindler et al., 1994; Schindler & Hadasik, 2000), but there is still lack of convincing hints for selection of the most appropriate model for particular application. However, the results of preliminary inverse analysis (figure 4) show that the investigated

steel does not soften during deformation at low temperatures. Therefore, the simplest version of the Hensel and Spittel (1979) equation was selected in the present work:

$$\sigma_p = A\varepsilon^n \exp(-q\varepsilon)\dot{\varepsilon}^m \exp(-\beta T) \qquad (2)$$

where: A, n, q, m and β - coefficients, T - temperature in °C.

Approximation of the flow stress curves using equation (2) was applied and the coefficients obtained from the approximation were used as starting point for optimization of function (1). Coefficients in equation (2) were determined by searching for the minimum of the objective function defined as a square root error between flow stress calculated from equation (2) and obtained from the preliminary inverse analysis. It allowed to decrease the computing times significantly. The coefficients obtained from optimization for the IF steel and the CuCr alloy are given in the first and the second row of table 1, respectively. The final value of the objective function (1), which can be referred to as the measure of the accuracy of the inverse analysis, is given in the last column of this table.

Table 1. *Coefficients in equation (2) for the IF steel and TRIP steel obtained from the inverse analysis.*

material	A	n	q	m	β	Φ
IF	641.0	0.3	0.0153	0.0159	0.00153	0.0663
CuCr	684.56	0.261	0.269	0.0224	0.	0.0565
TRIP	2367.8	0.433	1.181	0.0016	0.000762	0.0838

3.3. Inverse analysis for the TRIP steel

Similar analysis was performed for the samples assembled from the TRIP steel disks inserted in the IF steel tube or the CuCr tube. Knowing the flow stress of the tube materials the flow stress model for the TRIP steel was determined. The results of this analysis in the form of the flow stress are shown in figure 5. Full inverse analysis gave coefficients of equation (2) for the TRIP steel. They are presented in the last row of table 1.
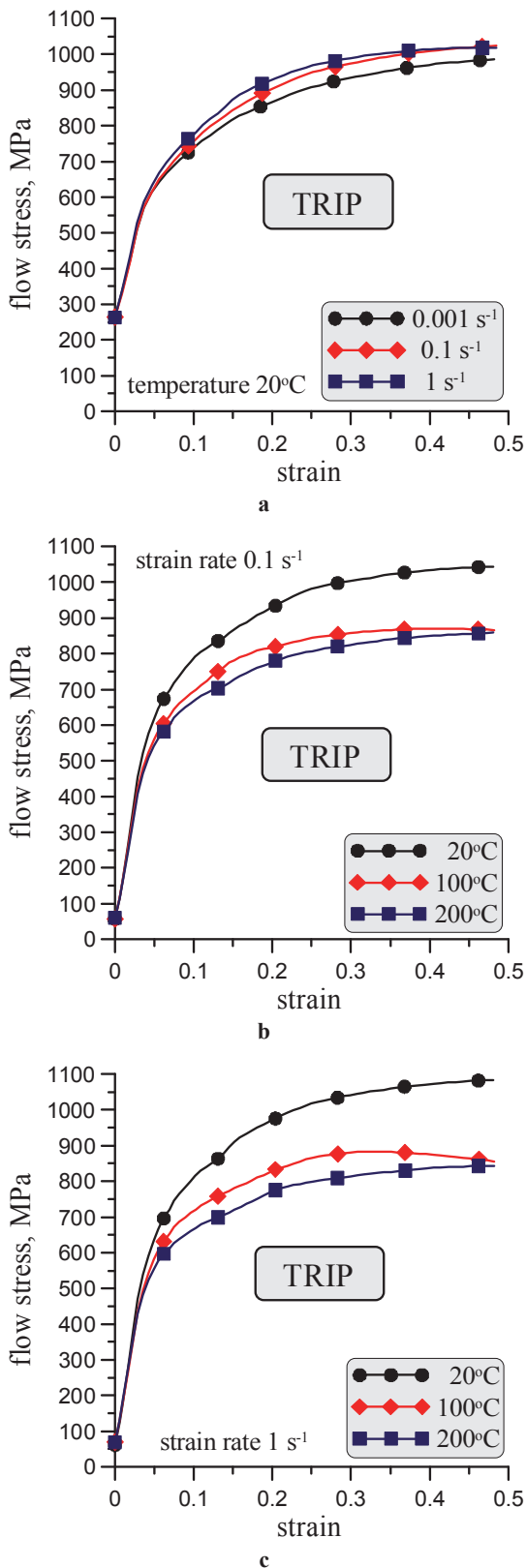
Fig. 5. *Flow stress vs. strain in tabular form determined in the first step of inverse analysis for the TRIP steel for the temperature of 20^oC (a) and the constant strain rate of 0.1 s^{-1} (b) and 1 s^{-1} (c).*

Decrease of flow stress for larger strains is the inaccuracy of equation (2). Since strains in bulk-sheet forming processes, as well as in stamping processes, can even exceed 1, application of equation

(1) for these processes can lead to erroneous results. Therefore, simpler model which is an extension of the Hollomon equation was additionally considered in the present paper:

$$\sigma_p = A\varepsilon^n \dot{\varepsilon}^m \exp\left[\frac{Q}{R(T+273)}\right] \qquad (3)$$

where: Q – activation energy.

As previously, the inverse method was applied to determine coefficients of equation (2) and these coefficients for the TRIP steel are given in table 2. It can be seen that in the investigated range of parameters the TRIP steel shows negligibly small sensitivity to the strain rate ($m = 0.003$) and small sensitivity to the temperature ($Q = 663.2$).

Table 2. *Coefficients in equation (3) for the TRIP steel obtained from the inverse analysis.*

TRIP Steel	A, MPa	n	m	Q, J/mol	Φ
	961.3	0.256	0.003	663.2	0.099

4. VERIFICATION AND VALIDATION OF THE MODEL

4.1. Verification of the model

Verification of the models was made by comparison of forces measured in the tests and calculated using the FE code with equations (2) implemented in the constitutive law. Figure 6 shows the comparison results for the IF steel. The results analysis shows that good accuracy was reached for the whole range of strain rates and temperatures.

Similar comparison of measured and calculated forces for the samples made of the TRIP steel disks in the IF steel sleeve was then performed and the results are shown in figure 8. Again equation (2) with coefficients in table 1 was used to describe flow stress of the IF and TRIP steels in the constitutive model. The analysis shows that accuracy is not as good as for solid IF steel samples but it is still acceptable.

4.2. Validation of the model

Flow stress values for the TRIP steel obtained from the tensile and compression tests are compared in figure 8. Apparently, for strains below 0.25 very good agreement between the results obtained from both tests is observed. Compression test gave realistic results up to the strain of 0.4. Above this value the strain lost its capability to constrain relative flow

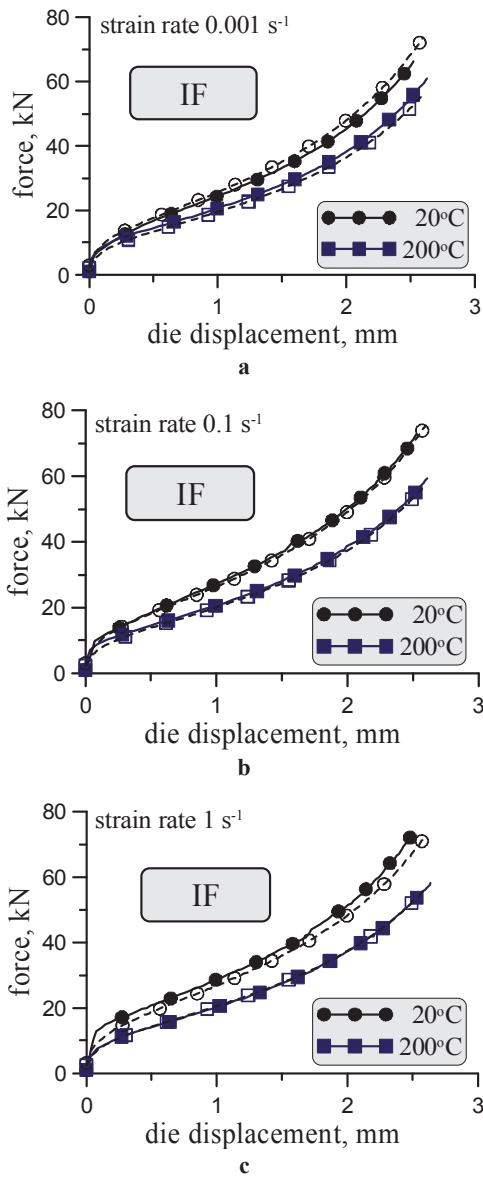of the disks, see cross section of the sample with the strain value of 0.9 (figure 10).

Fig. 6. *Comparison of measured vs. calculated forces (solid lines) using the FE code with equation (2) implemented in the constitutive law (dotted lines), for the strain rate of 0.001 s^{-1} (a), 0.1 s^{-1} (b) and 1 s^{-1} (c); IF steel.*
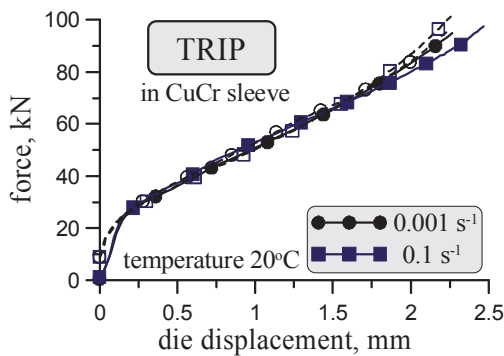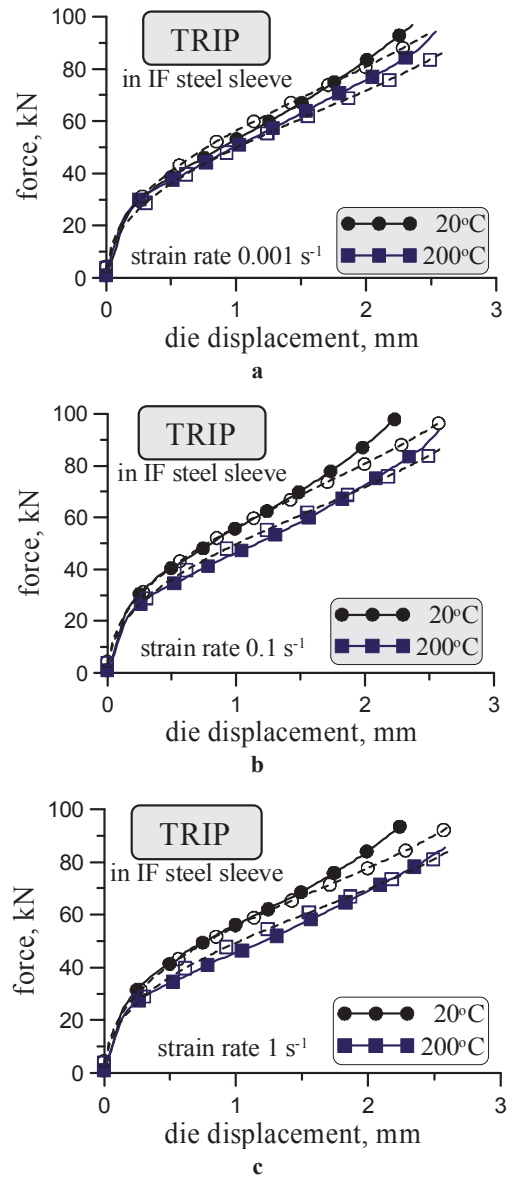

Fig. 7. *Comparison of measured forces (solid lines) with calculated using the FE code with equation (2) implemented in the constitutive law (dotted lines) at the temperature of 20°C for the strain rate of 0.001 s^{-1} and 0.1 s^{-1}; TRIP steel disks in the CuCr steel sleeve.*

Fig. 8. *Comparison of measured vs. calculated forces (solid lines) using the FE code with equation (2) implemented in the constitutive law (dotted lines), for the strain rate of 0.001 s^{-1} (a), 0.1 s^{-1} (b) and 1 s^{-1} (c); TRIP steel roundels in the IF steel sleeve.*
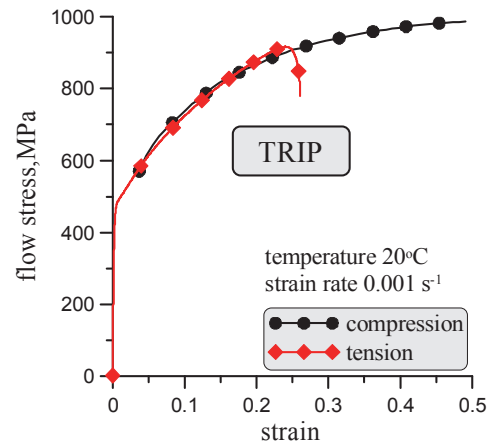

Fig. 9. *Comparison of stress-strain curve of compression test and tension test for the TRIP steel at temperature of 20°C and strain rate 0.001 s^{-1}. Flow stress in compression was determined by the inverse analysis for the TRIP steel roundels in the IF steel sleeve and in the CuCr sleeve.*
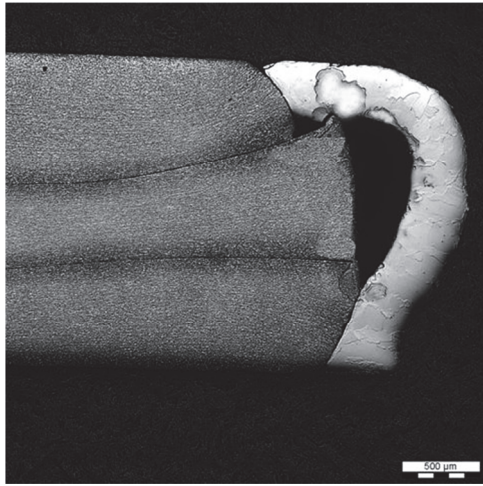
Fig. 10. *Cross section of the sample assembled of the TRIP steel disks in the IF steel sleeve after compression with the strain of 0.9.*

Flow stress model developed from the compression tests (equation (3) with coefficients given in table 2) was implemented in the FE code Abaqus and two processes were simulated. The first was stamping of a car body part and the second was orbital forming of a disc. The stamping process of a crash box element (part of the car body) was carried out in three stages. Cutting a hole in the part was not simulated. Subsequent steps considered in simulations are shown in figure 11. The results obtained from the numerical simulations were compared with the strains measurement in the part manufactured in one of the stamping company. Assuming the plane strain deformation, major and minor strains were measured and then compared with those obtained from the numerical calculations. The comparison results are shown in figure 12. The analysis of strains shows that locally they exceed maximum strain obtained in the tensile tests but they fall within the range of strains obtained in the compression of disks in a sleeve.
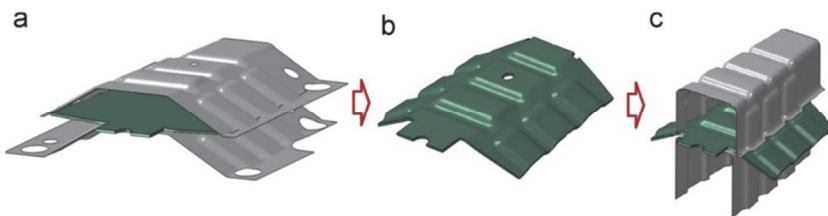

Fig. 11. *Steps in manufacturing of the car body part a) pre-stamping, b) cutting a hole, c) final stamping.*

The orbital forming was another process which was simulated using the material data obtained in the present work for the TRIP steel. This process consisted in changing the shape of the metal disk using

a rotary punch (Merklein et al., 2012). Reduction in force during the forming is the main advantage of the orbital forming, which is schematically shown in figure 13. Initial thickness of the TRIP steel strip was 2 mm.
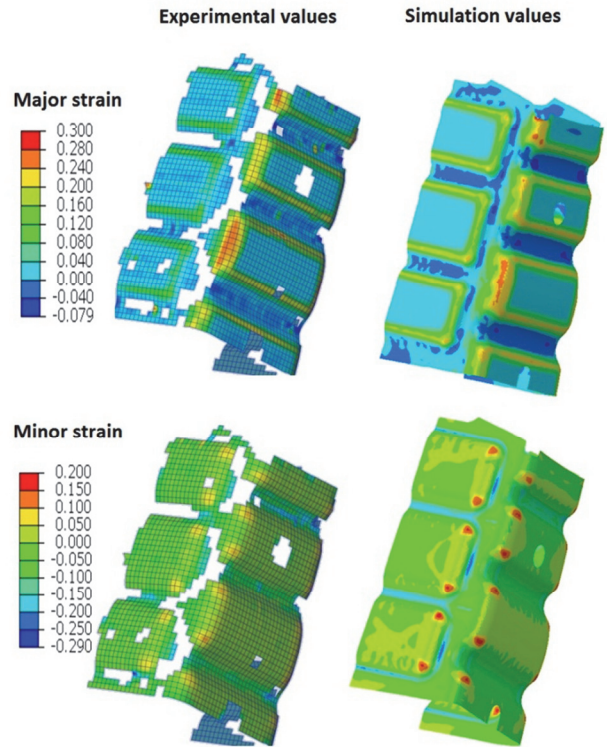

Fig. 12. *Comparison of measured main strain (Experimental values) with calculated using the FE code (Simulation values).*
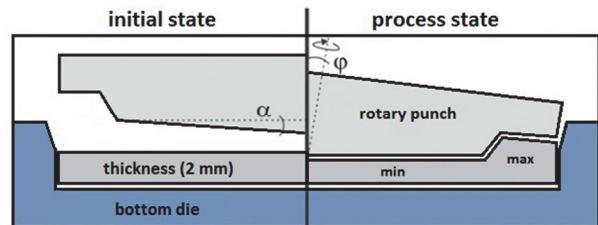

Fig. 13. *Schematic illustration of the orbital forming of the TRIP steel (α = 0.5°, φ = 0.5°).*

The final thickness of the disk varied between 2.6 mm at the rim and 1.55 mm in the centre. Calculated distribution of the effective strain is show in figure 14. In both considered processes it is seen that strains are much larger than in the stamping process and they exceed also those obtained in the compression of disks in a sleeve. It means that extrapolation beyond the experimental data was needed, but the range of this extrapolation was much lower for the compression of disks in a sleeve as compared with the tensile tests.
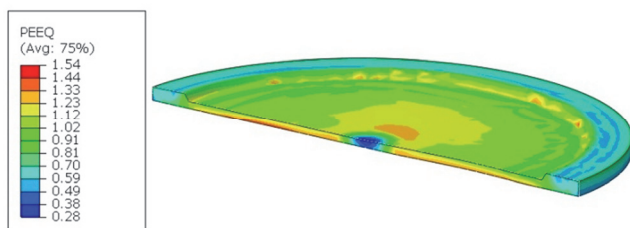
COMPUTER METHODS IN MATERIALS SCIENCE

Fig. 14. *Calculated distribution of the effective strain in the disk made by the orbital forming.*

5. CONCLUSIONS

− Compression tests for a pile of disks cut from the strip inserted in the IF steel or CuCr alloy tube sleeve allows to determine flow stress of the strip material to the strains of about 0.5.

− Test performed for the TRIP steel disks inserted in the sleeve allows to obtain larger strains as compared with the sample without a sleeve.

− Inverse analysis allows to eliminate the influence of the sleeve material and to determine real flow stress of the disk material.

− Very good agreement between the results from the tensile and compression tests was obtained for lower strains. It supports an opinion that, when the inverse analysis is applied, comparable results are obtained from different tests.

− In the investigated range of parameters, the TRIP steel showed negligibly small sensitivity to the strain rate and small sensitivity to the temperature.

− Due to its larger flow stress, larger deformations could be obtained for the CuCr alloy sleeve as compared with the IF steel sleeve. It is expected that application of the harder material for the sleeve would allow the total strain in the tests to increase even further.

ACKNOWLEDGEMENTS

REFERENCES

Banabic, D. , 2010, *Sheet metal forming processes: Constitutive modeling and numerical simulation*, Springer, Berlin, Heidelberg.

Gavrus A., Massoni E., Chenot J.L., 1996, An inverse analysis using a finite element model for identification of rheological parameters, *Journal of Materials Processing Technology*, 60, 447-454.

Gawąd, J., Kuziak, R., Madej, Ł., Szeliga, D., Pietrzyk, M., 2005, Identification of rheological parameters on the basis of various types of compression and tension tests, *Steel Research International*, 76, 131-137.

Gelin, J.C., Ghouati, O., 1994, An inverse method for determining viscoplastic properties of aluminium alloys, *Journal of Materials Processing Technology*, 34, 435-440.

Grosman, F., 1997, Application of the flow stress function in programmes for computer simulation of plastic working processes, *Journal of Materials Processing Technology*, 64, 1997, 169-180.

Hensel, A., Spittel, T., 1979, *Kraft- und Arbeitsbedarf Bildsamer Formgebungsverfahren*, VEB Deutscher Verlag fur Grundstoffindustrie, Leipzig.

Kowalski, B., Sellars, C.M., Pietrzyk, M., 2000, Development of a computer code for the interpretation of results of hot plane strain compression tests, *ISIJ International*, 40, 1230-1236.

Merklein M., Plettke, R., Opel, S., 2012, Orbital forming of tailored blanks from sheet metal, *CIRP Annals – Manufacturing Technology*, 263-266.

Merklein M., Hagenah H., Schneider T., 2013, Sheet-bulk metal forming processes - state of the art and its perspectives, Kolleck R., (ed.): *Proc. Conf. TTP 2013 - Tools and Technologies for Processing Ultra High Strength Materials*, Graz, 197-204.

Pietrzyk, M., 2000, Finite element simulation of large plastic deformation, *Journal of Materials Processing Technology*, 106, 223-229.

Schindler, I., Kliber, J., Boruta, J., 1994, Predikce deformacnich odporu pri vysokoredukcnim tvareni, *Proc. Conf. METAL*, Ostrava, 132-141.

Schindler, I., Hadasik, E., 2000, A new model describing the hot stress-strain curves of HSLA steel at high deformation, *Journal of Materials Processing Technology*, 106, 132-136.

Schneider, T., Merklein M., 2011, Sheet-bulk metal forming of preformed sheet metal parts, *Key Engineering Materials*, 473, 83-90.

Szeliga, D., Gawąd, J., Pietrzyk, M., 2006, Inverse analysis for identification of rheological and friction models in metal forming, *Computer Methods in Applied Mechanics and Engineering*, 195, 6778-6798.

Vegter, H., van den Boogaard, A.H., 2006, A plane stress yield function for anisotropic sheet material by interpolation of biaxial stress states, *International Journal of Plasticity*, 22, 557-580.

IDENTYFIKACJA MODELU NAPRĘŻENIA UPLASTYCZNIAJĄCEGO DLA MATERIAŁU W FORMIE TAŚMY PODDAWANEGO ODKSZTAŁCENIOM OBJĘTOŚCIOWYM

Streszczenie

W pracy rozważono problem wyznaczenia modelu naprężenia uplastyczniającego dla materiału w formie taśmy poddawanego dużym odkształceniom plastycznym. Wykonane zostały próby ściskania próbek zrobionych z krążków wyciętych z taśmy. Aby uniknąć przesuwania się krążków względem siebie umieszczono je w rurkach ze stali IF lub ze stopu CuCr. Naprężenie uplastyczniające stali IF i stopu CuCr wyznaczono na podstawie ściskania próbek cylindrycznych zrobionych z tych materiałów. Znając to naprężenie, zastosowano analizę odwrotną do identyfikacji modelu naprężenia uplastyczniającego stali TRIP na podstawie ściskania próbki z krążków umieszczonych w rurce. Opracowany model wykorzystano w symulacji dwóch procesów. Pierwszym było

COMPUTER METHODS IN MATERIALS SCIENCE

tłoczenie części nadwozia samochodu ze stali TRIP. Drugim przykładem był proces kształtowania elementu wykonanego z taśmy ze stali TRIP.