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FE AND PHYSICAL MODELLING OF PLASTIC DEFORMATION THE TWO-LAYER Mg/Al MATERIALS

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Abstract

The paper has presented the results of theoretical studies and experimental tests of the plastic deformation of two-layered Mg/Al specimens. Theoretical studies were carried out using the Forge2011® computer program. Physical modeling, on the other hand, was performed using the Gleeble3800 simulator. Cuboidal specimens with dimensions of 10x15x20 mm and a cladding layer thickness of 1.5 mm were cut off from the sheets obtained in the explosive welding method. The theoretical studies and experimental tests were carried out for the temperature range from 350 to 400°C and for different strain rates. Based on the obtained investigation results it has been found that the main parameters influencing the formability of two-layered Mg/Al materials are temperature and the strain rate.

Key words Mg/Al materials, plastic deformation, physical modelling, numerical modelling, FEM

1. INTRODUCTION

Magnesium and its alloys exhibit a number of advantageous properties: high strength to weight ratio, high dimensional stability, high thermal conductivity, good workability and castability (Kainer, 2004). However, insufficient corrosion resistance has limited the practical application of these materials (Przondziono et al., 2014). Aluminium and its alloys exhibit better corrosion ressistance compared to Mg alloys. Thus, the prospective solution is to manufacture Mg/Al multi-layer materials which will ensure increased corrosion resistance compared to homogeneous magnesium alloys. There are a lot of studies concerning the fabrication of Mg/Al bimetallic or Al/Mg/Al multi-layer materials by hot-pressing (Li et al., 2009; Zhu et al., 2011), extrusion (Tokunaga et al., 2012; Tokunaga et al., 2015), hot-rolling (Chang et al., 2009; Zhang et al. 2011), cold-rolling (Matsumoto et al., 2005) explosive welding (Mróz et al., 2015), twin-roll casting (Bae et al., 2011), in which the outer layer is either of pure aluminium or an aluminium alloy and can provide anticorrosive protection. In the case of joining two metals differing in formability, the method of selecting deformation parameters plays an important role. However, the available literature lacks information on the formability of two-layer Mg/Al materials. Paper (Luo et al., 2013) reports extensive studies concerning the three-layered Al/Mg/Al plates rolling process and determining the effect of heat treatment parameters on the thickness of intermetallic phases in the investigated materials. The obtained relationships for the effect of the heat treatment duration and temperature on the thickness of intermetallic phases, provided in the studies referred to above, can be described with parabolic functions, which can be used for selecting the diffusion bonding parameters. Based on the analysis of the investigation results it has also been found that the transition layers after the heat treatment process are brittle and that they have not been deformed plastically, but only fragmented during rolling.

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Since the beginning of the 21st century, attempts have been made to employ the hydrostatic extrusion process to the production of Mg/Al bimetallic bars (Kittner et al., 2010; Neugebauer et al., 2011). The analysis of the joint region in Mg/Al bimetallic bars showed that it included intermetallic phases that had formed as a result of the reactive diffusion phenomenon taking place at the joint interface. The thickness of the transition layer depended on the process conditions and was contained in the range from 10 to 35 μm. By analyzing the shape of finished bars and the transition layer region, an uneven distribution of the clad layer on the bar perimeter and length, and the fragmentation of intermetallic phases were found, which had affected the bond quality.

In the one of the first studies (Binotsch et al., 2014) where the formability of Mg/Al bars (in die forging) was determined, a Mg/Al bimetallic specimens obtained in the hot hydrostatic extrusion process were used. A hard and little ductile layer of Mg/Al intermetallic phases was formed at the Mg/Al bond interface. The Mg/Al specimens were deformed using different forging methods, namely: upsetting, spreading and rising. Although the test results showed a possibility of presetting large deformations, in some instances, however, intermetallic phase cracks occurred at the bond interface.

The authors' earlier work (Mróz et al., 2016) reports the results of tests for the plasticity of round AZ31 alloy specimens and for the effect of the aluminium cladding layer (in Mg/Al bimetallic specimens) on extending their formability range. The conducted experimental tests have shown that the application of the clad layer considerably extends the range of process parameters (such as temperature and strain rate), with which the AZ31 alloy can be deformed.

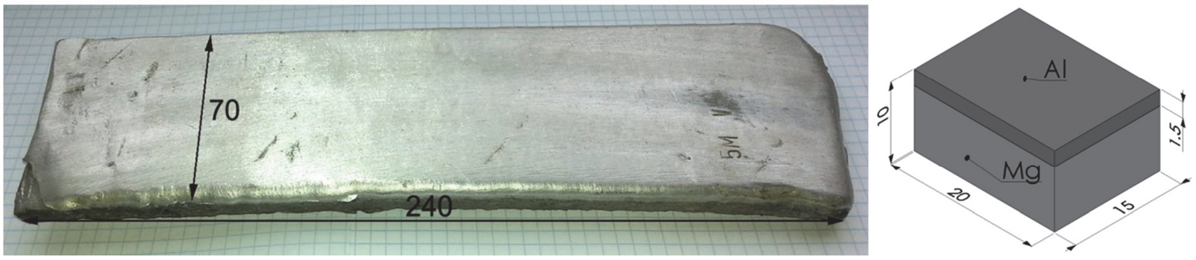
Thus, the aim of the study is to determine the effect of process parameters on the plastic deformation of two-layer Mg/Al materials. The paper has presented the results of theoretical studies and experimental tests of the plastic deformation of Mg/Al specimens. For the performed test the cuboidal specimens with dimensions of 10x15x20 mm and the initial thickness of Al layer 1.5 mm were used. Physical modelling was performed using the Gleeble3800 simulator. The thermo-mechanical simulation of the compression tests was carried out with the use of a visco-plastic model in the triaxial state of strain by using the Forge2011® program.

2. MATERIALS AND TESTING METHODOLOGY

Bimetallic specimens with the AZ31 thickness of 8.5 mm and AW-1050A aluminium layer thickness of 1.5 mm were manufactured using an explosive welding method (figure 1a). The explosive welding of bimetallic stocks was made in cooperation with the company Explomet (Poland). From the prepared bimetallic Mg/Al sheets cuboidal specimens with dimensions h=10 x w=15 x l=20 mm were cut (figure 1b).

The schedule of the compression test is shown in figure 2. Whereas, the study has limited itself to the analysis of the region situated under the anvil's immediate action, as the most heavily deformed (the region A in figure 2b).

The following parameters were adopted for the plastometric tests: relative deformation, 50%; strain rate, 0.1, 1, 10 s^{-1} and temperature, 350ºC and 400ºC. The temperature range was chosen based on the authors' earlier studies (Mróz et al., 2016) concerning the process of Mg/Al bimetal plastic working. It has been demonstrated that, due to the limited formability of the magnesium alloy, deformation at a temperature above 300°C advisable because of the possibility of the layer losing its continuity. The



a) b)

Fig. 1. Shape of Mg/Al stock after explosive welding – a) and a CAD model of the Mg/Al specimen used for the compression test – b)

physical modelling of the cuboidal Mg/Al specimen compression test were made for the verify results of the numerical modelling.

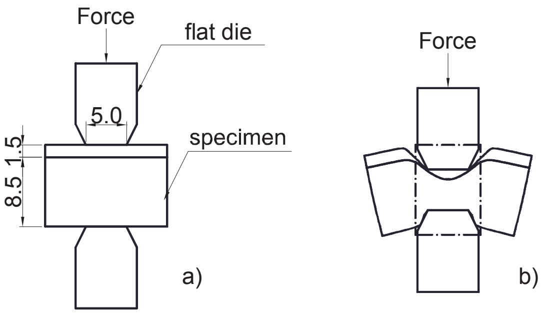


Fig. 2. *The schedule of compression test using the Gleeble3800 simulator – a) and the view of the analyzed area of the specimen after deformation – b)*

3. INITIAL PARAMETERS IMPLEMENTED FOR THE NUMERICAL MODELLING

The thermo-mechanical simulation of the compression tests was carried out with the use of a visco-plastic model in the triaxial state of strain by using the Forge2011® program, whereas the properties of the deformed material were described according to the Norton–Hoff (Norton, 1929; Hoff, 1954) conservation law. The application of the computer program Forge2011® using the thermo-mechanical models that it contains requires the definition of boundary conditions which are decisive to the correctness of numerical computation. The properties of individual bimetallic components have been determined in the authors' previous studies (Mróz, 2015). The tests in the Gleeble3800 simulator were planned so that the flow stress function and its coefficients could be developed for the conditions of the deformation process during a laboratory hot rolling.

For the description of the properties of the investigated materials, the Hensel-Spittel function (Hensel & Spittel, 1979) in the following form was employed:

$$\sigma_f = A_1 \exp^{m_1 T} \varepsilon^{m_2} \exp^{\varepsilon m_4} \dot{\varepsilon}^{m_3} (1+\varepsilon)^{\frac{m_5}{\varepsilon}} \exp^{\varepsilon m_7} \dot{\varepsilon}^{m_8 T} T^{m_9} \quad (1)$$

where: σ_f – flow stress [MPa], T – temperature [°C], ε – true strain, $\dot{\varepsilon}$ – strain rate [s^{-1}], A_1, $m_1 \div m_9$ – coefficients.

Based on the performed approximation of the results of plastometric testing of the materials used for the investigation with function (1), the values of the flow stress function coefficients were obtained, which are given in table 1.

Figure 3 shows sample plastometric testing results and plastic flow stress–strain curves and obtained from their approximation for the materials under investigation. The solid lines with empty markers denote the curves representing the plastometric testing results, while the solid lines with filled markers denote the curves obtained from the approximation of the plastometric testing results.

When analyzing the data in figure 3 it can be noticed that in the case of aluminium for the examined temperatures, the derived approximating equation describes the actual material with high conformity, both qualitative and quantitative. By contrast, for the Mg alloy, there occur significant differences, especially quantitative, between the actual testing results and the approximated data, in particular for the temperature 350°C. Therefore, for numerical examinations, a combined method was used, in which the rheological properties of the examined material are input in a tabular form (Mróz, 2008). This method allows actual data to be entered for the temperature–strain interval under examination, while for the remaining interval, the data is entered based on the results of plastometric testing approximation.

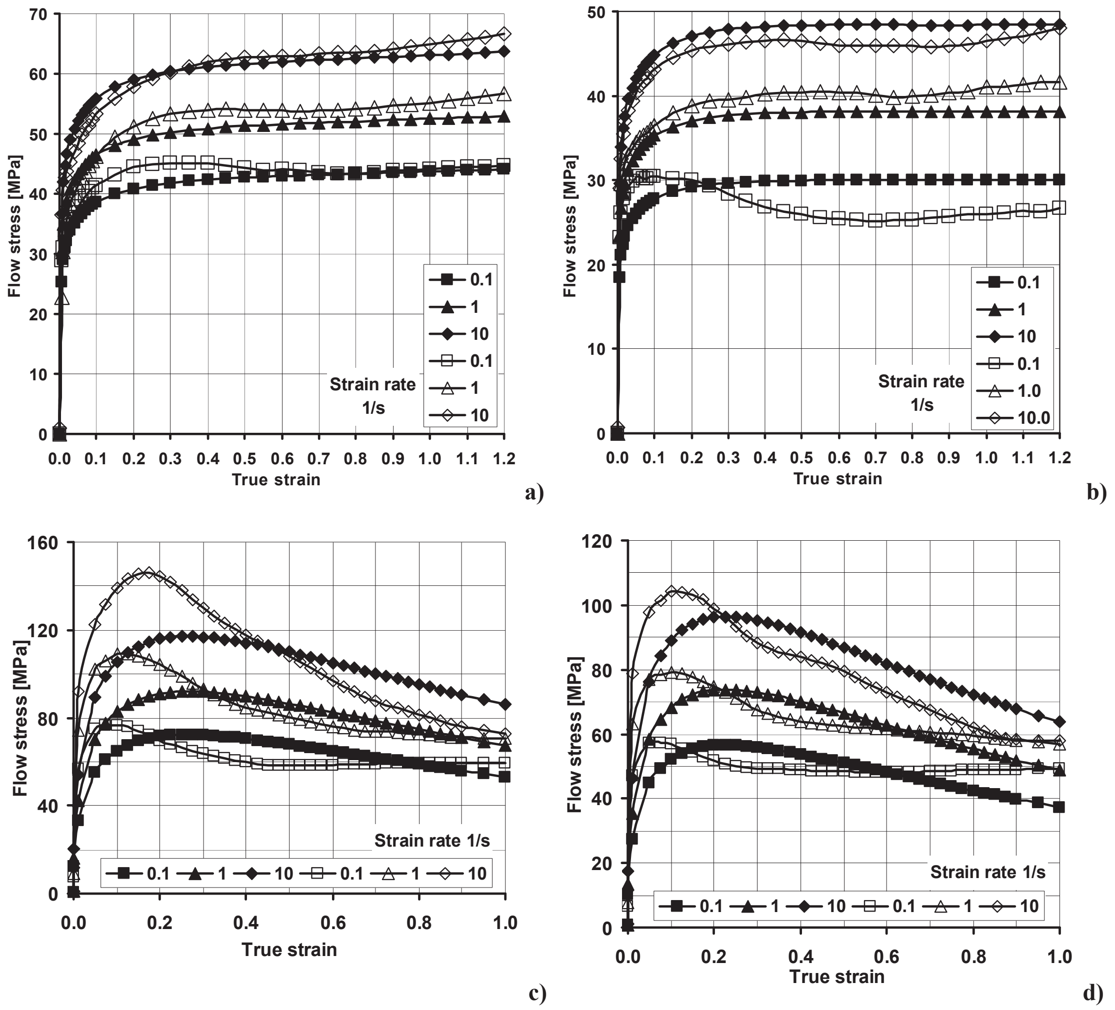
The use of the explosive welding method for making bimetallic stocks ensures a firm bond of the components to be achieved. Thus, in numerical simulations, the bond between the magnesium core and the aluminium cladding layer was defined as firmly adhering. The nodes of both meshes were not connected. In order to increase the speed and accuracy of computations, ¼ of the bimetallic specimen cross-section were used in the simulations.

The conditions of friction between the deformed Mg/Al bimetallic specimen were established based on the actual friction conditions prevailing at the contact between the working tool and deformed specimen surfaces (to reduce the friction, graphite

Table 1. *Coefficients of the flow stress function (1)*

Material	A_1	m_1	m_2	m_3	m_4	m_5	m_7	m_8	m_9
AW-1050A	0.08743	–0.0099	0.11325	–0.08845	–0.00058	–0.00153	0.196267	0.00048	1.71527
AZ31	0.68478	–0.0072	0.34242	0.02864	–0.08199	–0.00023	–0.00439	0.00022	1.41094

grease is used); friction coefficient, μ – 0.15. The physical modelling of the formability of the Mg/Al bimetallic material was conducted while preserving the constant average strain rate, which meant that with decreasing deformed specimen height, the working tool displacement speed changed. For the process of upsetting in the Gleeble3800 simulator, change in working tool speed is software determined based on the preset piston displacements in a specified time unit. On this basis it is possible to determine the relationship of the change in working tool linear speed in a time unit and to enter it in a tabular form to the Forge 2011® program for individual strain rates.



a)

b)

c)

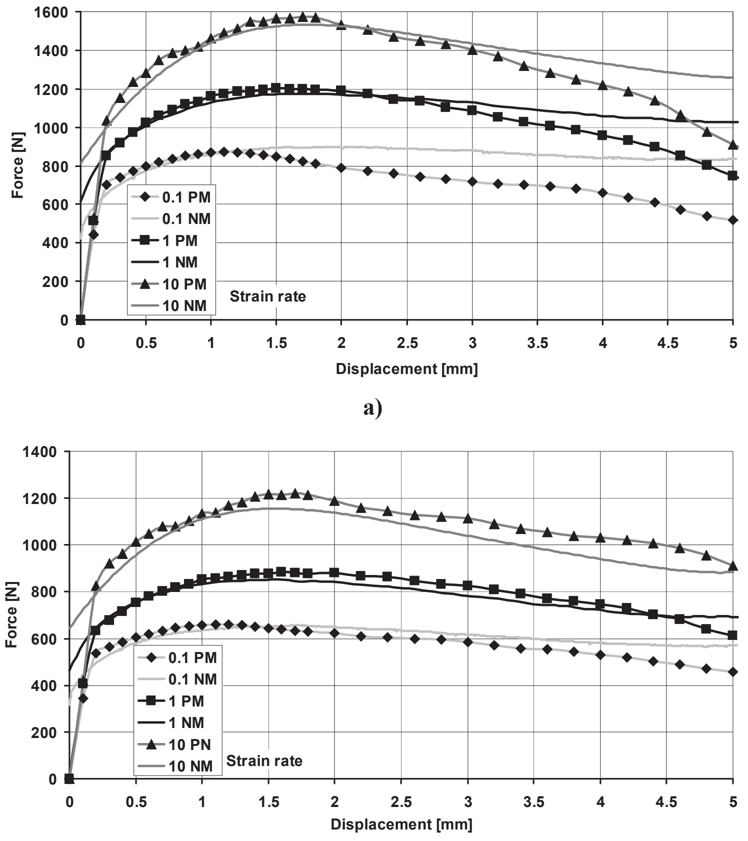
d)

Fig. 3. Flow stress curves of materials used for tests: a) aluminium, 350°C, b) aluminium, 400°C, c) magnesium alloy, 350°C, d) magnesium alloy, 400°C

4. RESULTS AND DISCUSSION

A parameter that enables the determination of the accuracy of obtained numerical computation results with experimental testing results is the force of working tool pressure on the specimen being deformed. Based on the results obtained in numerical and physical modelling, the relationship of the working tool force versus displacement was obtained. Based on the results obtained in numerical and physical modelling the dependence of the working tool force in the displacement was obtained (figure 4).

Figure 4 shows the diagrams of pressure force variation as dependent on the displacement for the examined strain rate and temperature ranges, plotted based on the results of numerical modelling (denoted by NM in the diagram) and physical modelling (denoted by PM in the diagram). From the data illustrated in figure 4 it can be noticed that the behaviour of all determined curves is similar for all cases examined. After attaining a force maximum for the characteristic displacement (true strain), a drop in pressure force value is observed. This is closely related with the properties of the matrix, i.e. the Mg alloy (figures 3c and 3d), where for true strains greater than approx. 0.2, a decrease in the value of plastic flow stress is observed. For the cladding material, i.e. Al (figures 3a and 3b), after attaining a maximum value, the plastic flow stress remains at a constant level or slightly decreases. When examining the data illustrated in the diagram, high similarity in the behaviour of the plasticity curves obtained at a temperature of 400°C (figure 4b) can be noticed. This is influenced by simplifications adopted for numerical modelling, which consist in disregarding the share of the intermetallic phase between the Mg phase and Al, as well as by microcracks occurring in the Mg alloy matrix (figure 10). It can be assumed, however, that in the range of deformations applied in the rolling process (up to approx. 35% of the reduction), the defined numerical model assures the sufficient accuracy of computations.



a)

b)

Fig. 4. *Force vs. displacement curves obtained from compression tests of Mg/Al bimetallic specimens: a) at a temperature of 350°C, b) at a temperature of 400°C*

To explain the effect of the adopted range of process parameters on the formability of Mg/Al specimens, numerical modelling of compression tests was performed. Figure 5 shows the Mg/Al specimen shapes obtained from compression test numerical computations.

By analyzing the data represented in figure 5 it can be found that the most deformed locations in the Mg/Al specimens are places that are under the direct effect of both the upper and the lower anvil. A slightly greater deformation of the cladding layer can be found for specimens deformed at a higher temperature (400°C). The application of the soft cladding layer on one specimen side only resulted in an uneven deformation of the Mg/Al specimens and their bending. In the case under examination, the specimen bend was taken as the measure of deformation unevenness. Figure 5 shows that with the increase in strain rate, the specimen bend increases, regardless of the temperature used. Also the increase in deformation temperature causes an increase in deformation unevenness. This phenomenon can be explained by the differences in plastic flow resistance between individual bimetal components, as shown in figure 3. The Al layer, which is characterized by a much lower plastic flow resistance compared to the Mg alloy, is more deformed. Thus, the plastic flow velocity of the Al layer increases compared to the plastic flow velocity of the Mg alloy layer. The uneven plastic flow of individual components over the height of a deformed Mg/Al specimen causes its characteristic bend.

To explain the effect of temperature–strain parameters on the plastic flow of Mg/Al specimens, the analysis of the normal stress component σ_y (figures 6 and 7) and the tangential stress component τ_{xy} (figures 8 and 9) of the stress tensor was made.

Figures 8 and 9 show that with the increase in strain rate, the value of compressive stress in the Mg/Al regions directly affected by the working anvil parts increases. By contrast, the temperature increase causes a decrease in compressive stress, which appears directly from the plastic flow curves for the individual bimetal components (figure 3), as well as from the values obtained for the Mg/Al specimens (figure 4). Whereas, due to the fact of the lower plastic resistance of the Al layer, irrespective of the deformation temperature, the distribution of compressive stress towards the specimen centre is more intensive on the Al layer side. The increase in strain rate causes also an increased influence of compressive stress in the central specimen regions, which is caused by a faster increase in the plastic flow resistance of the Al layer with the increase in strain rate values. This results in an uneven stress distribution over the height of specimens being deformed, which, as a consequence, affects the plastic flow of individual bimetal components.

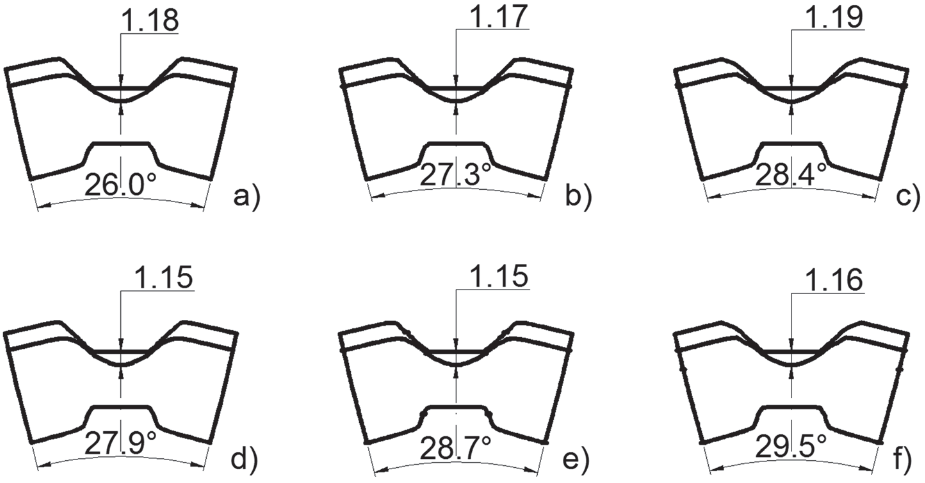


Fig. 5. *View of Mg/Al cross-section specimens after numerical modelling of compression tests: a) 350°C, strain rate 0.1* s^{-1}*, b) 350°C, strain rate 1* s^{-1}*, c) 350°C, strain rate 10* s^{-1}*, d) 400°C, strain rate 0.1* s^{-1}*, e) 400°C, strain rate 1* s^{-1}*, f) 400°C, 10* s^{-1}

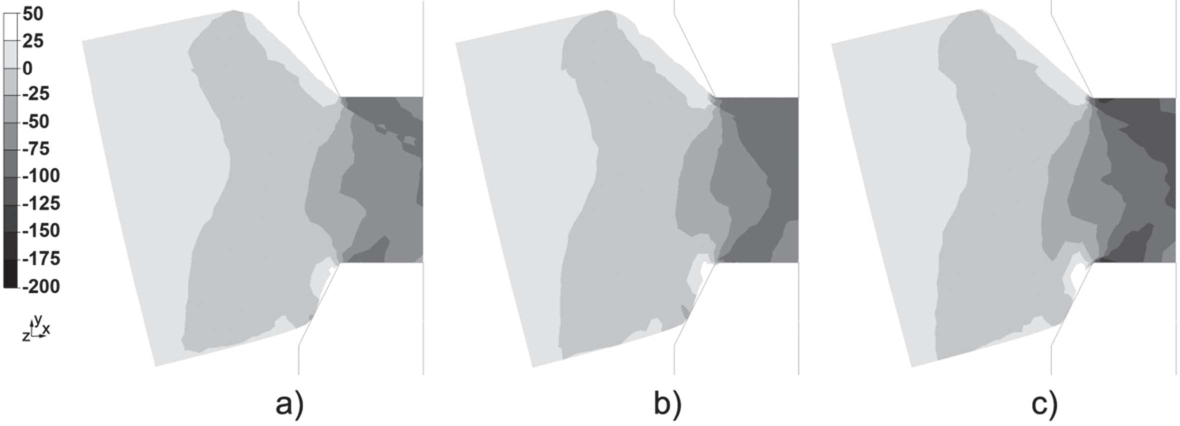


Fig. 6. *Distribution of the component* σ_y *normal stress in the Mg/Al specimens after compression tests (at a temperature of 350°C): a) strain rate 0.1* s^{-1}*, b) strain rate 1* s^{-1}*, c) strain rate 10* s^{-1}*, (1/2 of the specimen)*

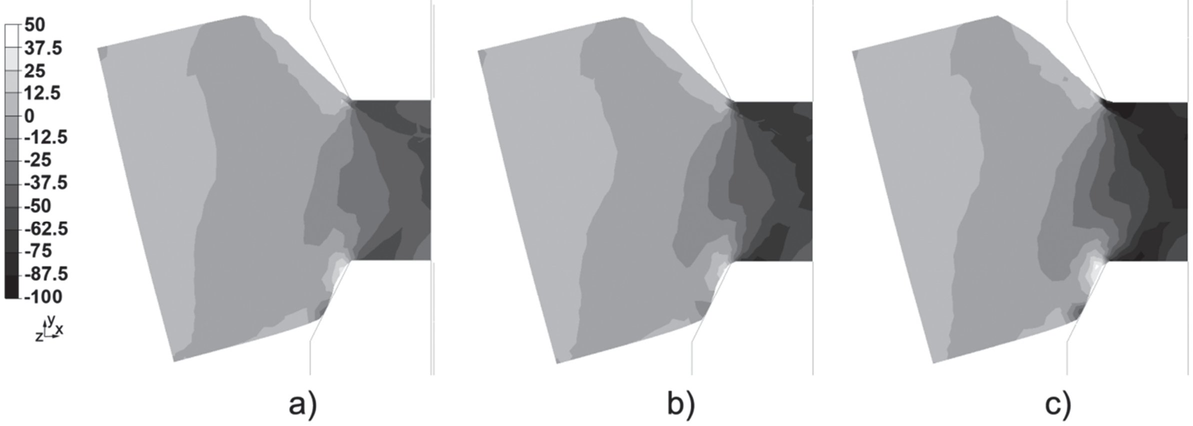


Fig. 7. *Distribution of the component* σ_y *normal stress in the Mg/Al specimens after compression tests (at a temperature of 400°C): a) strain rate 0.1* s^{-1}*, b) strain rate 1* s^{-1}*, c) strain rate 10* s^{-1}*, (1/2 of the specimen)*

During the compression test, a characteristic forging cross appears in the deformed specimens, which causes tangential stresses to occur in the most heavily deformed regions, which cause the shear of the material. Figures 8 and 9 show the distribution of the tangential stress component τ_{xy} for the examined temperature–deformation parameters.

The use of the soft cladding layer disrupts the symmetrical tangential stress distribution. Figures 8 and 9 show that with the increase in strain rate, the

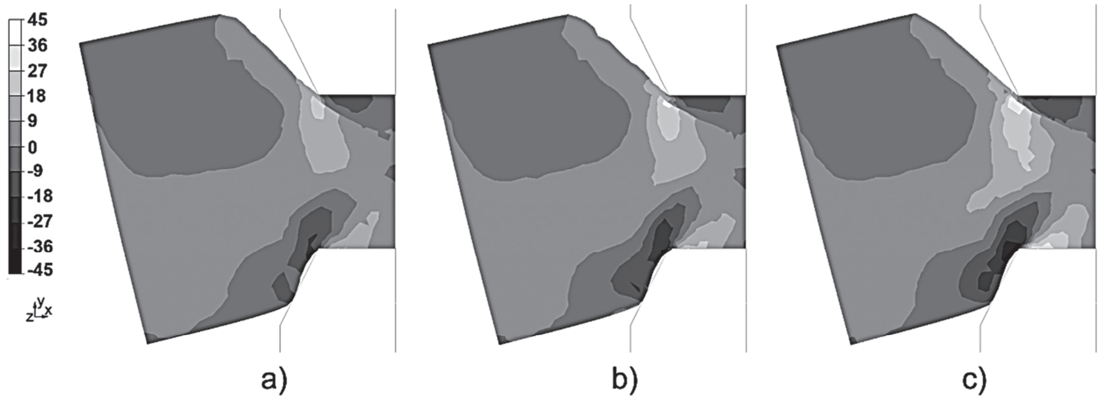


Fig. 8. Distribution of the component τ_{xy} tangential stress in the Mg/Al specimens after compression tests (at a temperature of 350°C): a) strain rate 0.1 s^{-1}, b) strain rate 1 s^{-1}, c) strain rate 10 s^{-1}, (1/2 of the specimen)

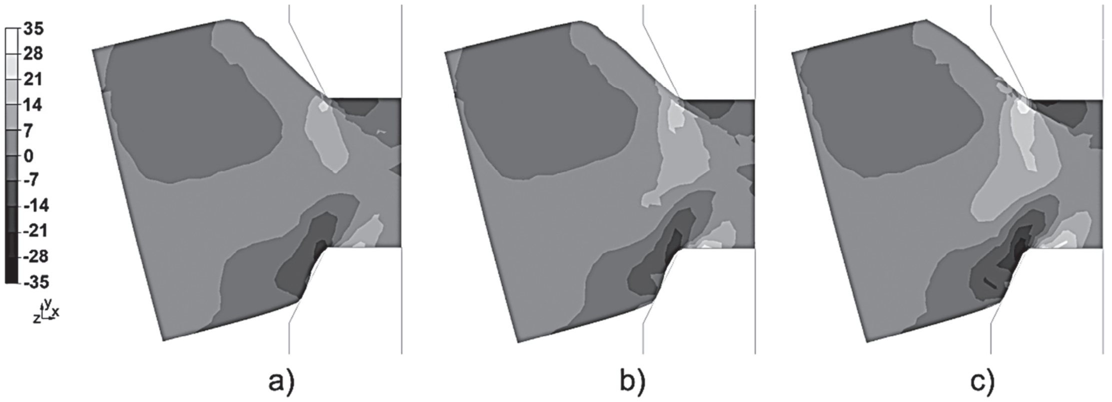


Fig. 9. Distribution of the component τ_{xy} tangential stress in the Mg/Al specimens after compression tests (at a temperature of 400°C): a) strain rate 0.1 s^{-1}, b) strain rate 1 s^{-1}, c) strain rate 10 s^{-1}, (1/2 of the specimen)

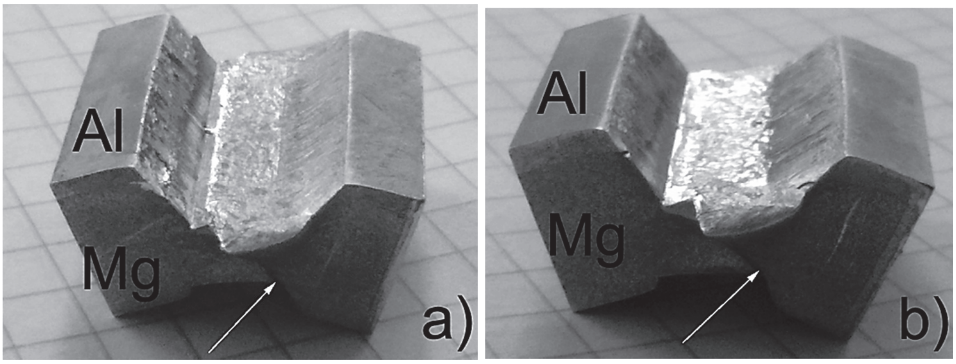


Fig. 10. View of the Mg/Al samples after compression tests, (at a temperature of 400°C): a) strain rate 1 s^{-1}, b) strain rate 10 s^{-1}

value of tangential stress and its affected region increase, which is especially visible for the Mg alloy layer on the cladding layer side. The increase in the value of tangential stress due to the increase of strain rate and the decrease of the process temperature causes intensive shear bands to occur in those regions, which significantly contribute to structure refinement. The absence of the cladding layer causes unfavourable tensile tangential stresses to occur in the Mg alloy layer directly affected by anvil, which, in extreme cases, initiate microcracks in the Mg alloy layer (figure 10). When examining the shape of the specimens after compressive testing, their characteristic bend towards the Mg layer can be found, which is consistent with the numerical computation results.

The application of the outer Al layer makes the accumulation of tangential stresses take place in the cladding layer. The aluminium used is more ductile compared to the Mg alloy, which creates the possibility of extending the range of temperature–deformation parameters (an increased strain rate and a reduced temperature), at which materials of this type can be deformed. Thus, it can be stated that the use of a soft cladding layer increases the formability of the AZ31 alloy.

6. SUMMARY

The method relying on numerical and physical modelling was providing the complete information on the deformed Mg/Al materials and allows the comprehensive analysis of the plastic flow of its components. Based on this data, it will be possible to select the process parameters that will be used in the different metal forming processes, for example rolling. The investigations carried out have indicated a considerable potential for deforming Mg/Al type bimetallic materials, being greater compared to the AZ31 alloy.

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SYMULACJA MES I MODELOWANIE FIZYCZNE ODKSZTAŁCALNOŚCI DWUWARSTWOWYCH MATERIAŁÓW MG/AL

Streszczenie

W pracy przedstawiono wyniki badań teoretycznych i doświadczalnych plastycznego odkształcenia dwuwarstwowego materiału Mg/Al. Badania teoretyczne przeprowadzono za pomocą programu komputerowego Forge2011®, natomiast modelowanie fizyczne wykonano za pomocą symulatora Gleeble3800. Badaniom poddano próbki prostopadłościenne o wymiarach 10x15x20 mm i grubość warstwy platerującej 1,5 mm. Dwuwarstwowy materiał, z którego pobrano próbki otrzymano metodą zgrzewania wybuchowego. Badania teoretyczne i doświadczalne wykonano dla zakresu temperatur od 300 do 400°C oraz dla różnych prędkości odkształcenia. Na podstawie otrzymanych wyników badań stwierdzono, że głównymi parametrami wpływającymi na odkształcalność prętów bimetalowych Mg/Al są temperatura oraz prędkość odkształcenia.

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