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EXPERIMENTAL INVESTIGATIONS AND NUMERICAL MODELS OF TOOL STEEL DURING SEMISOLID FORMING

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Abstract

The main aims of the work were to determine material characteristics of cold work tool steel, grade 210CR12 in semisolid forming conditions, as well as developing of numerical model of this steel. Moreover, possibilities of application of Computational Fluid Dynamic methods and solid mechanics modelling techniques were tested. Methodology and results of experimental investigation is described. The results of experiments were then utilized for developing series of numerical simulations. Two sets of simulations are presented, based on the Computational Fluid Dynamics or solid mechanic modelling methods. Comparison of experimental and numerical results is presented, as well as comparison of CFD and structural mechanics based numerical models.

Key words: cold work tool steel, thixoforming, numerical modelling

1. INTRODUCTION

Thixoforming of steels has been under development for less than twenty years. Some properties of thixoforming seem to be very attractive, especially when connected with high mechanical properties of steel products. Unfortunately, there are a lot of serious obstacles in industrial application of this technology. The most important issue, which distinguishes thixoforming of steels from aluminium alloys, is forming temperature.

Temperatures range of semi-solid forming (called "temperature window") for steels lies between 1250°C and 1530°C, varying with steel grade chemical compositions. It is challenging for tools, which is followed by high costs. Phase segregation and narrow temperature window are big obstacles, when possibility of near-net-shape forming is the biggest advantage (Hirt & Kopp, 2009).

Having in mind the difficulties with application of steel in thixoforming, it is necessary to conduct basic analysis on suitability of specific grades of steel in thixoforming process. In this article a preliminary analysis for the 210CR12 steel is described. Some attempts to numerical modelling of thixoforming of this steel are presented. Some numerical models based on the solid state mechanics and Computational Fluid Dynamic (CFD) is shown.

2. EXPERIMENTAL INVESTIGATION

Testing of steel in a semisolid state is difficult. The tests applied typically for metals in solid state (in view of plastic working) as well as liquid state (casting) do not provide reliable results. On the other hand, tests typical for semi-solids are difficult to perform and they require hardly available instrumentation. An attempt was made at the Institute for Fer-

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rous Metallurgy to develop a research methodology for alloys in the semi-solid state on the basis of Gleeble 3800 simulator. Primary works by Sołek (2004) covered analysis of aluminium alloys. Results of these works formed the basis for launching of research on analysis of steels in semi-solid state. The first stage of the research was aimed at selection of steel, which could be formed by means of thixoforming and at the same time would be easily available on the market and desired by consumers.

2.1. 210CR12 steel

The selected steel grade is a cold-work tool steel with chemical composition shown in table 1. High chromium alloyed tool steels (usually with 12 wt.% Cr, other carbide forming elements and high carbon content) are known as ledeburite steels. Hard carbides of eutectic origin are typically present in these steels (Behúlová et at., 2009).

Table 1*. Chemical composition of 210CR12 steel grade.*

C	Mn	Si	P	S	Cr	Ni	Mo	W	V	Cu
1.80	0.15	0.15	Max 0.03	Max 0.03	11.00	Max 0.35	Max 0.20	Max 0.20	Max 0.15	Max 0.35
2.10	0.45	0.40			13.00					

The aspects which control the selection of steel are twofold. The first is its characteristics within the range of solidification temperatures – gentle settling is desired, not a rapid transform. The second is its structure, which does not require preliminary preparation of thixoforming process (contrary to e.g. some aluminium alloys). Reasonably wide scope of liquidus - solidus temperature is important (theoretical calculations for the analysed steel resulted in the range of approximately 40°C). Similar steel, X210CrW12 was investigated i.e. by Shimahara et al. (2006).

NST

Nil strength temperature (NST) is one of the most important characteristics of metals, especially when processes near solidus take place. NST is a temperature, at which the alloy loses its strength due to formation of weak or liquid phases along grain boundaries.

NST is evaluated by heating specimens measuring ϕ6x82 mm to the temperature 100°C below solidus at the rate of 20°C/s, and then heating at the rate of 1°C/s to rupture. The specimen is mounted in a special testing instrument and during the test is loaded with fixed force of approximately 80 N (air-ram). The NST temperature is a temperature of specimen at the moment of rupture.

Tension test

Tension test is evaluated by heating of ϕ10x123.5 mm specimen up to the chosen temperature, maintaining for 5 s and then extension by 20 mm at the rate of 20 mm/s.

Hot compression

In hot compression (HC) tests ϕ10x123.5 mm specimen is heated at the rate of 20°C/s up to 1150°°C and at the rate of 1°C/s to chosen temperature. Then specimen is maintained in this temperature for 6 seconds. Finally, specimen is compressed with constant velocity of 20 mm/s. The stroke is 3 mm or 7.5 mm.

Moreover, two specimens were kept in forming temperature 1200°C for respectively 60 and 180 seconds to verify an influence of initial microstructure on material flow during forming.

2.2. Results

NST

5 consecutive NST tests were performed. The results are shown in figure 1. The mean value of the NST computed on the basis of the tests is 1209.8°C and the standard deviation is 5.1°C.

Tension tests

Six tests were performed in 1200, 1250, 1270, 1300 and 1320°C. Results of these tests are shown in figure 2.

Hot compression

Compression tests are divided in three groups. Specimens compressed by 3 and 7.5 mm at different temperatures are respectively the first and the second group. The third one are three tests of compression in 1200°C, preceded by preheating in forming temperature for 6, 60 and 180 seconds. Results of compression tests are presented in figures 3–5, while selected examples of specimens after processing are shown in figure 6.

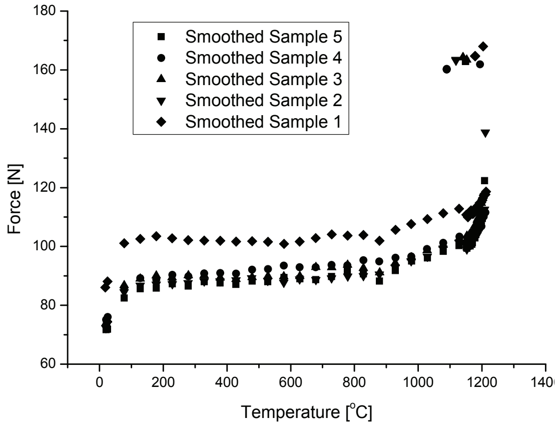


Fig. 1. *Force as a function of temperature during NST test.*

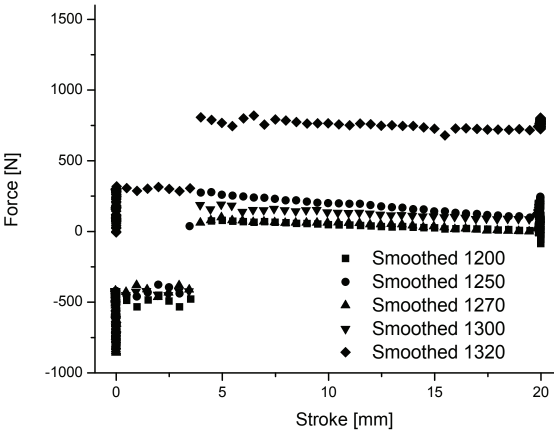


Fig. 2. *Force in function of stroke in tension test.*

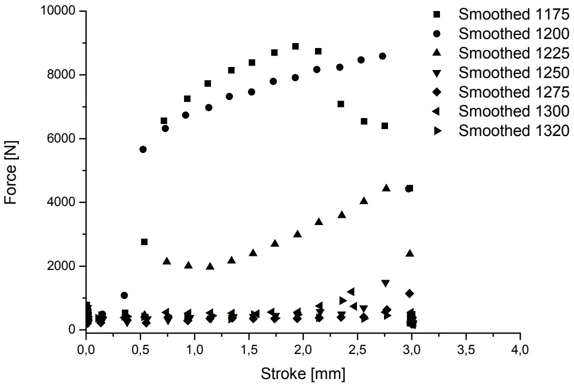


Fig. 3. *Compression force for the first tests' group.*

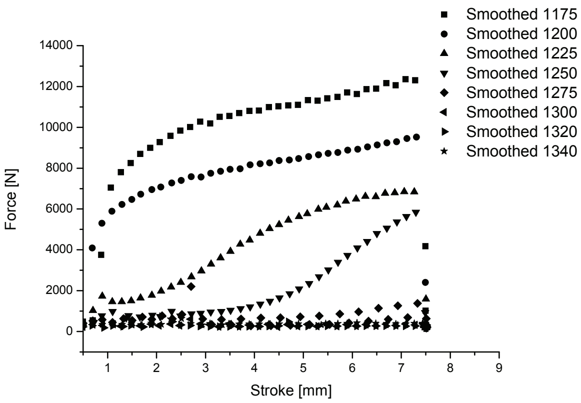


Fig. 4. *Compression force for the second tests' group.*

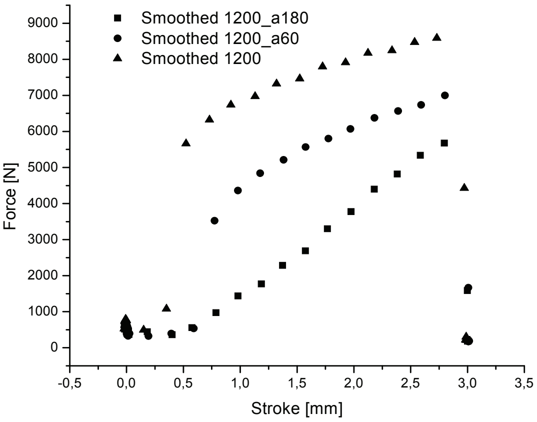


Fig. 5. *Compression force for third tests' group.*

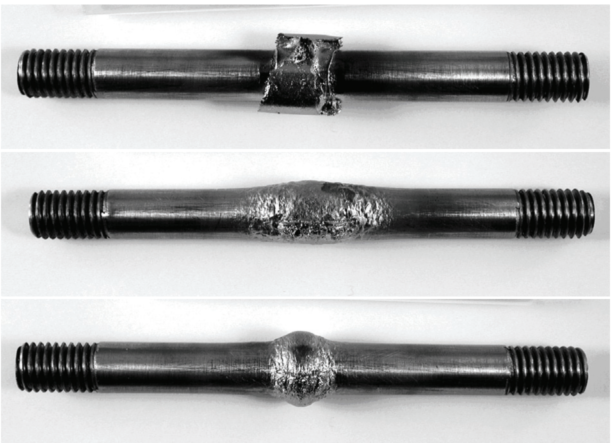


Fig. 6. *Examples of specimens after compression.*

2.3. Discussion

NST

Results of all tests are consistent. Standard deviation at the level of 5°C validates the correctness of the results.

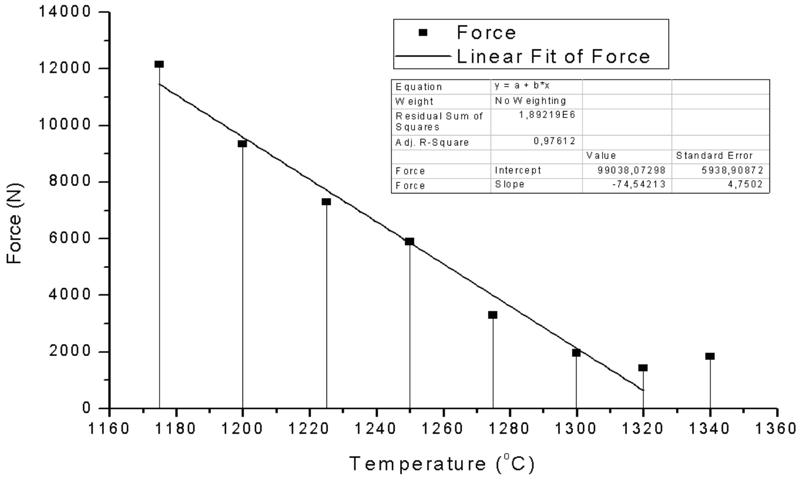
Tension test

The results of tensile tests are hardly interpretable. Uniform, slowly decreasing values of forces were obtained during these tests. Unfortunately, measured forces are incompatible with expectations. Acquired values are chaotic, whereas a decrease of forces with increasing temperature was expected. Moreover, values of the forces are noticeably smaller than in the case of hot compression. In the view of obtained results, the tensile tests cannot be considered as reliable.

Hot compression test

Upsetting results may be separated into two individual scopes. Compression curves for temperatures below 1250°C indicate increase of force during upsetting. Those results could be interpreted as an effect of hardening of material during the deformation or deformation of regions with lower temperature. The remaining curves do not show a similar effect. A separate description is required for the results for the temperature range above 1250°C. In the initial phase of upsetting (compression Δh = 3 mm and initial part for Δh = 7.5 mm) no increase of forces is observed. In the second phase, the specimen behaves similarly to those at smaller deformation temperature. These results may be justified by the extrusion of the eutectics in the first phase and deformation of fixed grid in the second phase.

Maximal values of the forces during upsetting are depicted in the figure 7. For the temperature range below 1320°C these forces are characterized by linear dependency with respect to temperature. During the upsetting in the temperatures of 1320°C and 1340°C, the forces tend to increase with the temperature, which is interpreted by the authors as a measurement error.



Equation	y = a + b*x		
Weight	No Weighting		
Residual Sum of Squares	1,89219E6		
Adj. R-Square	0,97612		
		Value	Standard Error
Force	Intercept	99038,07298	5938,90872
Force	Slope	-74,54213	4,7502

***Fig.** 7. Top forces during hot compression with 7 mm stroke and in linear approximation (last point is excluded from the approximation).*

Obtained results could be compared to those presented by Hirt and Kopp (2009) for similar steel, X210CrW12. Due to differences in chemical composition and different specimens shape, exact quantitative comparison is not possible. Qualitative comparison shows similar effect of rapid decrease of forming forces when critical temperature is exceeded.

The objective of the last test was comparison of forces during upsetting for different preheating at selected temperature. Decrease of yield stress with increasing time is clearly seen, whereas the slopes of force curves in the second phase of the process are very similar.

3. NUMERICAL MODELLING

Semi-solid forming processes, like thixoforming, rheocasting, some continuous casting variants and some others, merges phenomena from fluids and solids behaviour. High deformation and time dependent properties of materials are causes that neither structural, nor fluids computational methods are suitable. Structural solutions are commonly based on Lagrangian motion description and remeshing is required when mesh becomes too distorted. Remeshing dramatically increases time consumption and decreases solution accuracy. In the other hand, Computational Fluid Dynamics methods, based on Eulerian or Arbitrary Lagrangian Eulerian motion descriptions, are not suitable for history dependent materials behaviour modelling.

In this paper, two kind of numerical models are presented: based on structural mechanic for lower temperatures and based on CFD for processes in higher temperatures. Compatibility of CFD methods with viscous, non-Newtonian fluids and structural mechanics based solutions with viscoplastic material was proved by Zienkiewicz & Cormeau (1974). However, in solids computations, dynamic effects are usually omitted. In forming with high speed, like in thixoforming, dynamic effects are significant, what had been shown by Sołek et al. (2005).

On the other hand, during thixoforming, thixotropic effects are often not apparent. There are many works, which adapts numerical models neglecting time-dependent effects and still obtaining correct results (Messmer et al., 2007; Kim & Kang, 2000; Huilgol & You, 2009).

Presently developed models, both structural and CFD based, neglects thixotropic behaviour.

3.1. Structural mechanic based models

Commercial FEM code ADINA was used. Computations were focused on lower temperatures (up to 1250°C). Analyzing of forming forces in lowest range, up to 1200°C suggest that material behaves typically for deformation in solid state. Initially, deformation force increases almost linear. It could be interpreted as elastic deformation. In second part of process, deformation has plastic character. It is not sure, what is the cause of increase of force. It could be caused by hardening, by deformation of regions with lower temperature and higher yield stress or both of them simultaneously. In this work, a classical temperature dependent bilinear elastoplastic model is chosen. Experiments were conducted for only one deformation rate, than rheological model is dependent only on temperature and strain. Computations were performed for the 3D part of the upper part of specimens. Cross-section on the bottom of model is a symmetry plane and is fixed in vertical direction. Upper surface of the specimen moves vertically with given displacement in both horizontal directions. No thermal boundary convection is assumed. Computational results are shown in figure 8. Due to some disadvantages of ADINA based model, preliminary simulation with Forge3D were developed.

3.2. Computational Fluid Dynamics based methods

CFD based numerical models were developed with ADINA-CFD software. Formed metal in solid state was assumed to be liquid with very high viscosity. In temperatures above solidus temperature, temperature dependent power law model had been chosen. Numerical model of hot compression test was developed. Computations were performed for the 2D axisymmetric model of the upper part of specimen. Cross-section on the bottom of model is a symmetry plane where normal velocity is equal to zero, while tangential velocity is not constrained. Velocity on upper surface is equal to tool speed (20 mm/s). There is no thermal boundary convection. Initial conditions includes: (i) uniform gradient of temperature, varying from 50°C on upper specimen surface to forming temperature on the cross-section plane; (ii) velocity in axial direction equal to tool velocity. Volume of Fluid (VOF) method was used for traction of free surface.

3.3. Results

Structural mechanic based models

Two criterions of experimental and numerical results are chosen: (i) agreement of forces on a piston and (ii) the shape of deformed part of specimen. Parameters of numerical model had been nominated with inverse analysis. Comparison of computed and measured forces is shown on figure 8. It could be seen, that obtained agreements is satisfactory. Forces in both stages of deformation are correctly predicted, as well as disappearing of linear dependent deformation in temperature 1225°C. Prediction for temperature 1175°C is correct. Unfortunately, in higher temperatures, computed shape is wrong.

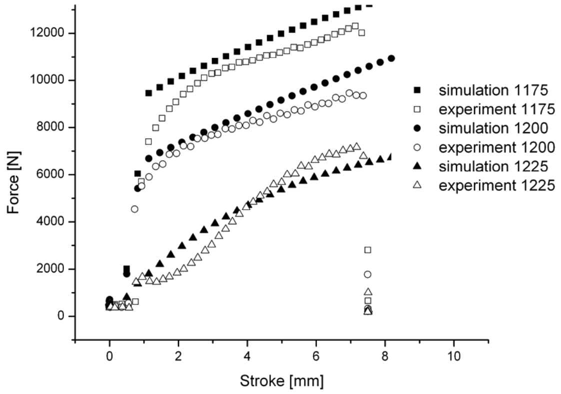


Fig. 8. *Comparison of computed and measured forces.*

To obtain better agreement of computed and actual shape, material model had been revised. Introducing very rapid decrease of yield stress and hardening coefficient between 1175°C and 1200°C led to better shape prediction. Unfortunately, ADINA software does not have remeshing capabilities, therefore computations have to be interrupted after mesh distortion.

Preliminary computations with remeshing had been provided with Forge3D software. Simplified material model had been used and quantitative results of computations could not be compared with experimental data. Although the predicted shape of formed specimen is very similar to experimental one (figure 9).

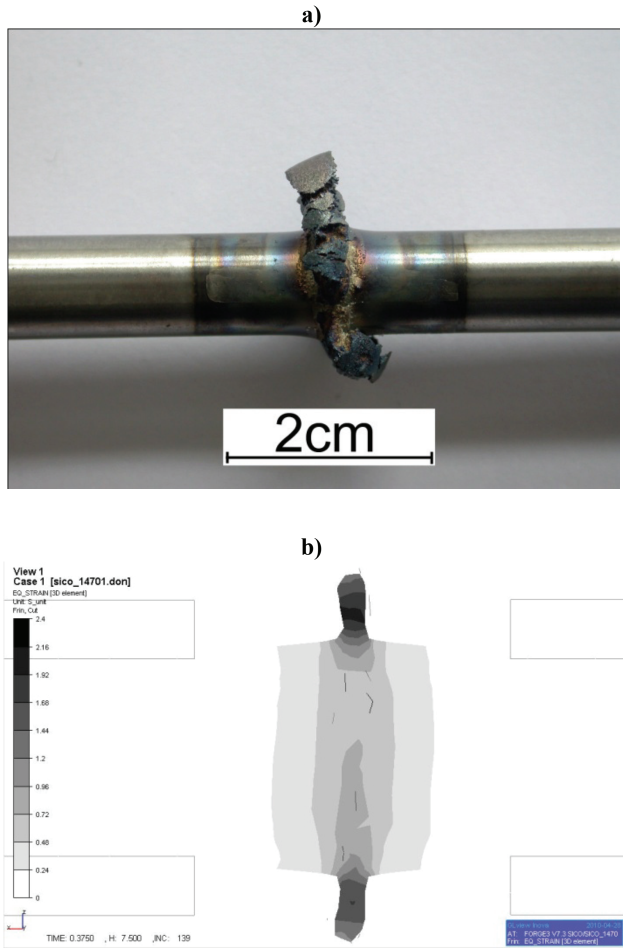


Fig. 9. Specimen compressed in 1250°C (a) and numerical simulation in Forge3D (b).

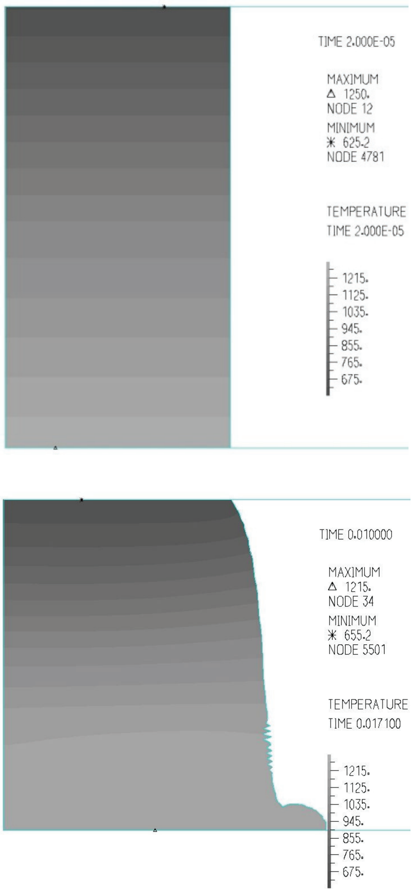


Fig. 10. Shape of the specimen predicted with CFD method; solid and liquid regions taken into account.

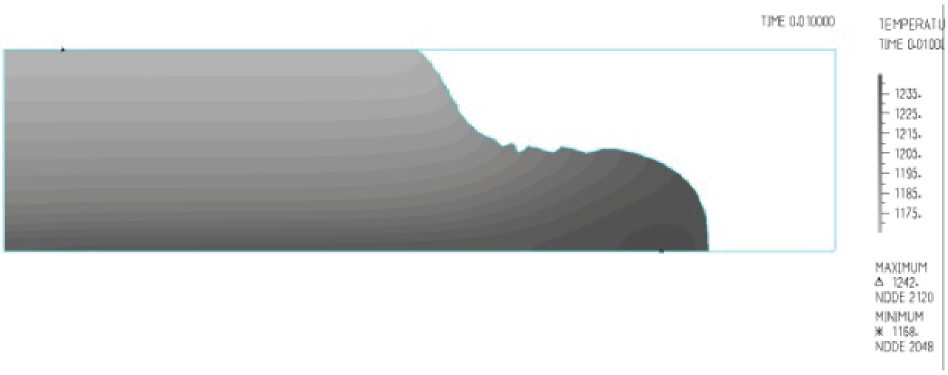


Fig. 11. Shape of the specimen predicted with CFD method; only liquid region taken into account.

3.4. Computational Fluid Dynamics based methods

Experimental results do not provide reliable values of forming forces. Therefore, presently only the shape of deformed specimen could be used for results comparison.

As it was mentioned before, VOF methodology has been used, so the shape of specimen could not be strictly mapped. It was assumed, that the shape is approximated with an isosurface of fraction function C equal to 0.5.

In the first variant of computations, both solid and semisolid regions are taken into consideration. Results of computations are shown on figure 10. It could be seen, that 'solid' part is expanding, which is not observable in experiment. It is an effect of modelling of solid metal with extremely high, but finite, viscosity. The second variant includes only semisolid part. Predicted shape is closer to experimental, but the main disadvantage of this method is a'priori assumed border between semisolid and solid parts (figure 11).

4. DISCUSSION AND FURTHER WORKS

All presented methods do not satisfy the requirements. Computations based on ADINA structural methods do not reproduce the shape of formed specimen correctly. Model in Forge3D is more promising. Viscoplastic material model probably will allow achieving proper solution. Nevertheless, remeshing will be a significant obstacle in modelling of very high deformations, increasing time of computations and approximation error. CFD methods have also serious disadvantages. Firstly, modelling of solid part is difficult and not very accurate. Secondly, application of multiscale models is difficult. On the other hand, a possibility of CFD methods in modelling of thixoforming with closed dies has been proved (i.e. Macioł & Pietrzyk 2010).

In the future, Forge3D software will be used for modelling of free deformation. Multiscale models will be developed and integrated with Forge3D. CFD techniques will be used in modelling of closed dies forming.

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BADANIA EKSPERYMENTALNE ORAZ MODELE NUMERYCZNE STALI NARZĘDZIOWEJ PODCZAS FORMOWANIA W STANIE STAŁO-CIEKŁYM

Streszczenie

Zasadniczym celem pracy było wyznaczenie charakterystyk stali narzędziowej 210CR12, formowanej w warunkach stałociekłych, a także opracowanie modeli numerycznych dla tej stali. Ponadto, zweryfikowane zostały możliwości stosowania metod dynamiki płynów (Computational Fluid Dynamics, CFD) oraz metod modelowania odkształcania ciał stałych do modelowania procesów formowania w stanie stałociekłym. Opisane zostały metodologia oraz wyniki prac doświadczalnych. Wyniki te zostały wykorzystane do opracowania symulacji numerycznych. Przedstawiono symulacje oparte na metodach CFD oraz oparte na modelach ciał stałych. W pracy porównano wyniki osiągnięte za pomocą metod doświadczalnych i symulacyjnych, jak również porównano wyniki uzyskane z metod CFD i strukturalnych.

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