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Rheological properties of alloys near solidus point intended for thixoforming

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Thixoforming processes are more and more popular in automotive industry. At present, the shaping a lot of components from cast aluminium alloys in the semi-solid state is performed and possibility of application of both wrought aluminium and steel alloys is investigated. The main goal of this work is the analysis of the rheological properties of metal alloys at high temperatures, just below the solidus point, and in the semi-solid state with low liquid phase content. The data obtained from the analysis can form the basis of numerical simulation for designing and optimizing the thixoforming processes. The rheological properties should be known over a wide temperature range so that the simulations could also predict defects such as incomplete die filling. The analysis concerned both aluminium alloys (A356, 7075) and a steel alloy (M2). The paper also discusses development of globular microstructure in partially melted alloys.

Keywords: *thixoformnig, globular microstructure, rheological properties, material test, physical modelling*

1. Introduction

The shaping of the material in the thixoforming processes is realized in the solidification temperature range. The combination of the semi-solid state and globular microstructures provides a material with thixotropic properties. Thixoforming processes operate more efficiently at conditions of forming where uniform temperature of the material is assured. However, in real industrial versions, such as thixoforging and thixocasting the uniform distribution of temperature in the formed metal alloys is not fully ensured. One reason of uneven temperature distribution is due to the intensive cooling of the material by the much lower temperature of the tools. The cooling can be intensive enough for the outer temperature of the material being formed to decrease below the solidus point during the dynamic part of the forming process. Note that thixoforming is normally carried out at fraction liquid between 20–50% [1, 2]. Numerical simulations require knowledge of the rheological properties of the alloys being shaped in order to predict both the correct pressure variables of the process and the correct die filling front. The rheological properties should be known over a wide temperature range so that the simulations could also predict defects such as incomplete die filling. This paper presents experiments, based on the compression test, used to measure the rheological properties both in the solidification temperature range and below solidus temperatures. The experiments were executed in Institute for Ferrous Metallurgy in Gliwice on the Gleeble 3800 simulator using the Hydrawedge unit (Figure 1) [3]. In order to obtain more uniform temperature distribution and avoid oxidation a protective atmosphere was applied. The compression tests on the Gleeble® system are possible in semi-solid state approximately up to 20% liquid fraction.

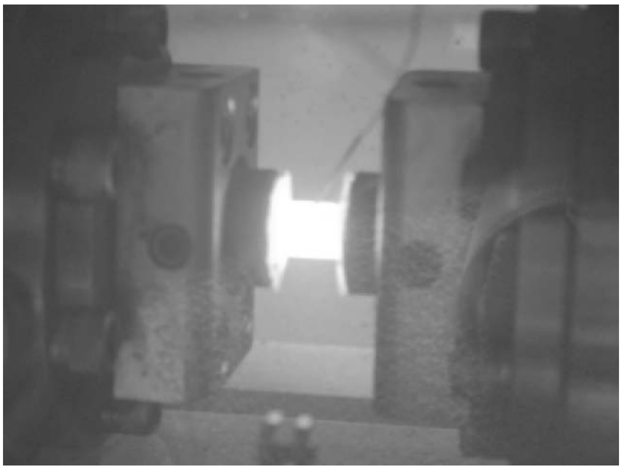

Fig. 1. Sample in the vacuum chamber before the compression test on the Gleeble® system during heating

2. Rheological properties of aluminium alloys near solidus point

Rheology of metallic alloys in semi-liquid state is commonly defined by means of flow stress or apparent viscosity in relation to equations of motions, for which the rheology is being established. Nevertheless both these values for such condition are strong functions of temperature, strain velocity, and time (metal in semi-liquid state demonstrates qualities of non-Newton and thixotropic liquids). With such defined approach, effect of strain has secondary significance considering domination of flow mechanisms showing low sensibility to this parameter. Gleeble system usually records stress – strain function during plastometric tests. However, in case of axial symmetric samples upset forging, it is relatively simple to determine relation of tool force and its displacement. Relation of tool forces and displacement can be used for estimation of apparent viscosity model parameters for alloys being analysed. Samples of 10 mm height and 12 mm diameter have been used in upset forging tests. Figure 2 illustrates stress – strain curves for A356 alloy. The relations shown were obtained for strain rate 10 s^{-1}.

The alloy for testing had globular microstructure obtained in process of semi-continuous casting with simultaneous magnetohydrodynamic stirring of solidifying alloy (MHD method) [4]. This method consists in forming of strong rotational electromagnetic field within crystalliser causing intensive mixing, which in effect prevents development of dendritic microstructure. Two samples were upset forged in temperatures below solidus point (500, 550 °C), while the next two in temperatures above solidus point (560, 565 °C). Lack of strain magnitude influence on stress is observed for temperature 565 °C. This fact proves that considering relatively high content of liquid phase, flow constitutes mechanism of forming. Plot of stress in temperature 560 °C shows sudden magnitude increase, preceding its uniform decreasing. Strain mechanism in the first phase consisted in destroying of solid phase particles crystal skeleton. Material flow prevailed in the final phase. Upset forging tests at temperatures 560 °C and 565 °C were performed with small portion of liquid phase, amounting approx. to 5–10%. Low portion of liquid phase in alloy causes difficulties in process control. Increasing of forming temperature by 5 °C (from 560 to 565 °C) gave 5-times decrease of maximum flow stress (Figure 2). Taking into consideration that temperature difference obtained in die cavity can reach 3–4 °C, thixotropic forming of tested A356 alloy would be, in fact, very difficult in these temperatures.

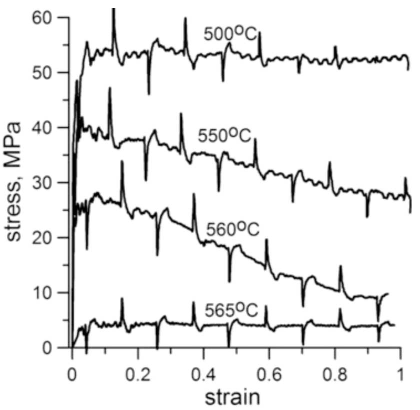

Fig. 2. Stress-strain curves for A356 aluminium alloy at temperatures near solidus point

Next the compression tests were carried out for 7075 aluminium alloy. Also, in this case, the alloy had the globular microstructure, which was obtained using the SIMA (Strain-Induced Melt Activated) method [5]. This method can be relatively easy employed for plastic metal alloys. Also, it can be applied for steels, giving good results [6]. Globular microstructure is formed in the highly strained alloy during partial melting. Starting material for this method is cast alloy of dendritic structure. Such alloy subjects to hot working (in temperature higher than recrystallizing temperature). Finally, strained alloy is partially melted to semi-solid state. Recrystallization process takes place in the material during heating, and when solidus temperature is exceeded, liquid phase penetrates boundary of recrystallized grains, causing fragmentation of solid phase. As a result globular microstructure built of equiaxial, fine grains, is obtained. Experimental works have shown that this size largely depends on strain when in solid state, and on soaking time in semi-solid state. The advantage of this method is possibility of purchasing of metal alloys that are plastic pre-strained, at very affordable prices.

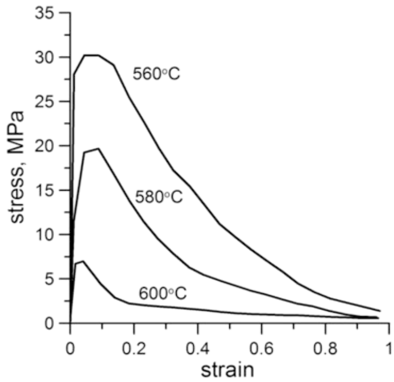

Fig. 3. Stress-strain curves for 7075 aluminium alloy at temperatures near solidus point

Flow stresses recorded for 7075 alloy are shown on Figure 3. All compression tests were performed for semi-solid state, while portion of liquid phase increasing together with temperature caused resistance decrease of solid phase particles skeleton, as well as increase of flow portion in strain mechanism. Upset forging test of 7075 aluminium alloy was performed in temperature range 560–600 °C, which corresponds to theoretically calculated 15–30% portion of liquid phase. At upset forging temperature 560 °C maximum stress reached approx. 30 MPa, while after increase of upset forging temperature up to 600 °C its value decreased down to approx. 7.5 MPa, i.e. 4-times.

3. Rheological properties of steel alloys near solidus point

The analysis of rheological properties of M2 tool steel near solidus point was the next part of the work. Prior to compression tests, a DSC-TGA analysis was carried out to estimate the solidus, liquidus temperatures and transformation reactions which are caused by phase changes. The DSC-TGA heating curve is shown in Figure 4. An analysis was carried out in the Institute of Metallurgy and Materials Science PAS in Kraków. The solidus is estimated at 1230 °C and the liquidus at 1450 °C. The DSC-TGA curve exhibits three major endothermic peaks which are caused by transformation reactions. The first and the second peaks of this curve are associated with the end of the carbides dissolution, while the third is the end of austenite dissolution.

Also, in the case of M2 steel alloy, the globular microstructure was obtained using the SIMA method. The flow stresses recorded for different temperatures are shown in Figure 5. A measurement was carried out for the strain rate of 10 s^{-1} at each temperature. Three tests are carried out for the solid state (1190, 1210, 1225 °C) and three for the semi-solid state (1235, 1245, 1300 °C). For the solid state, one can observe a decrease of the flow stress for an increase of temperature. The flow stress for 1225 °C is lower by one third. For the semi-solid state, an increase of the liquid fraction under the influence of an increase of temperature causes a decrease of resistance of the solid particles skeleton and an increase of the liquid flow in the deformation mechanism. Compression tests in the semi-solid state for M2 steel alloys were carried out at a temperature range of 1235–1300 °C to be related to the liquid fraction of 5–15%. For a deformation temperature of 1235 °C, the maximal stress amounts to 95 MPa, and after being heated to 1300 °C, its value decreases to a level of about 50 MPa, that is twice.

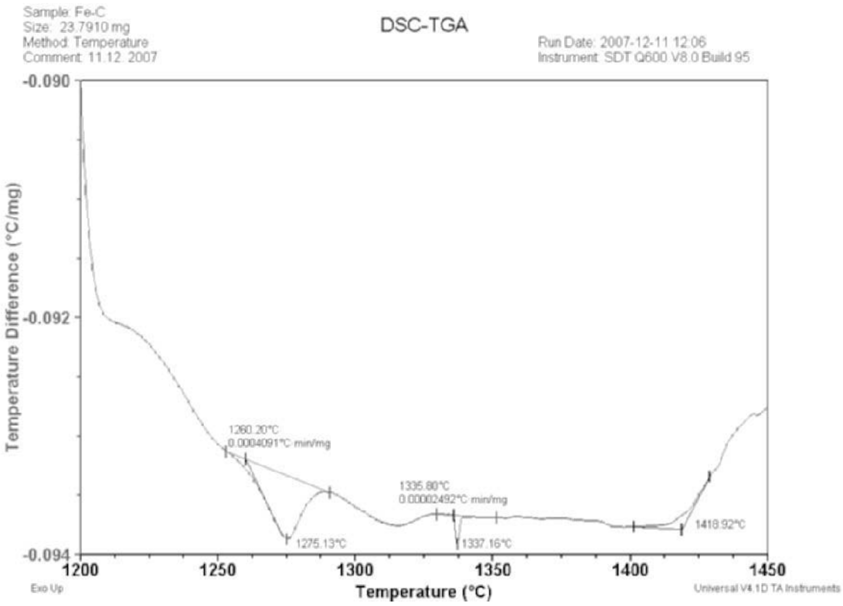

Fig. 4. DSC-TGA heating curve for M2 tool steel

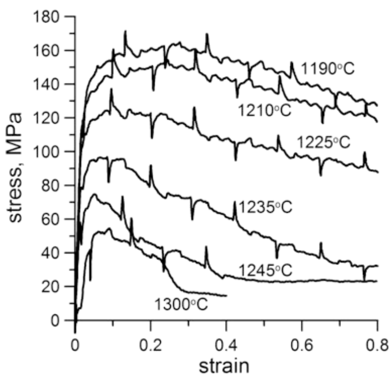

Fig. 5. Stress-strain curves for M2 tool steel alloy at temperatures near solidus point

During the experimental work an influence of the strain rates changes on the flow stresses was investigated. The flow stress is highly sensitive to changes of the strain rate. Therefore, in the solid state, the material shows viscoplastic rheological properties and in the semi-solid state, viscous properties.

4. Microstructure analysis in M2 tool steel after heating to a semi-solid state

Within the confines of this work, an analysis of microstructure evolution in hot forged tool steel after heating to a semi-solid state was carried out. The supplied material was in the form of a hot forged rod of 80 mm in diameter. The heating experiments were carried out using the Hydrawedge unit of the Gleeble® system. The geometry of the samples was the same as the geometry used for the compression test (10 mm in diameter, 12 mm in height). The samples were heated in an argon gas environment to reduce oxidation. The heating speed was 5 °C/s. The control thermocouple was welded to the surface in the middle of sample.

The samples were heated to 1250 °C and 1300 °C, and after heating, they were quenched in water to freeze the structures. Figure 6a and 6b show the structures at the above-mentioned temperatures. The structures show solid grains surrounded by traces of the liquid matrix. The liquid fraction includes mostly carbides. One can observe that a higher temperature gives more traces of the liquid fraction both inside solid grains and along their boundaries.

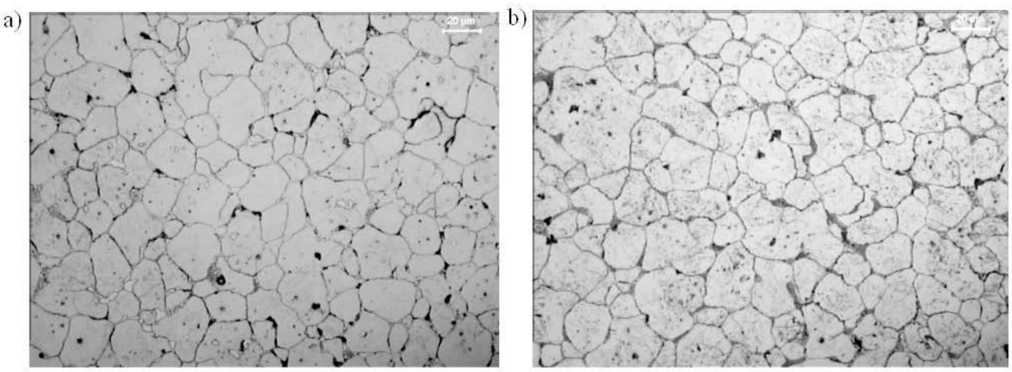

Fig. 6. Optical micrograph of M2 steel at (a) 1250 °C and (b) 1300 °C at zero minute holding

5. Summary

Thixoforming technology is very sensitive to process conditions. It results from the phase change connected with the solidification that proceeds under the influence of the cooling of shaped alloys. The experiments carried out in this work show that a small change of temperature causes a significant change of the flow stress, even a few times. Therefore, owing to the instability of thixoforming processes, problems with their control can occur. Design and optimization require determination of the ranges of process parameters to avoid defects of products. This is why knowledge of the rheological properties in a wide range of process parameters is very important.

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Własności reologiczne stopów metali formowanych tiksotropowo w temperaturach bliskich punktowi solidus

Procesy formowania tiksotropowego są coraz bardziej popularne w przemyśle motoryzacyjnym. Obecnie kształtuje się w stanie stało-ciekłym dużo części z odlewniczych stopów aluminium, jak również prowadzi się badania nad wdrożeniem formowania tiksotropowego plastycznych stopów aluminium oraz stali. Celem pracy była analiza własności reologicznych stopów metali w temperaturach bliskich punktowi solidus zarówno w stanie stałym, jak również stało-ciekłym z małym udziałem fazy ciekłej. Wyniki przeprowadzonych badań mogą być zastosowane w symulacjach numerycznych w ramach projektowania i optymalizacji procesów formowania tiksotropowego. Analiza dotyczyła zarówno stopów aluminium (A356, 7075), jak również stali (M2). W pracy poddano analizie rozwój mikrostruktury globularnej w stanie stało-ciekłym w stopie stali.