A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
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THE APPLICATION OF THERMODYNAMIC CALCULATIONS FOR THE SEMI-SOLID PROCESSING DESIGN [1)]

ZASTOSOWANIE OBLICZEŃ TERMODYNAMICZNYCH DO PROJEKTOWANIA PROCESÓW FORMOWANIA W STANIE STAŁO-CIEKŁYM

Semi-solid metal processing is now a commercially successful manufacturing route producing lots of near net-shape parts. One member of such processing technologies is thixoforming which is based on the special behaviour of alloys with non-dendritic microstructure in the partially liquid state. The semi-solid processing design requires the use of faithful values of thermodynamic material properties. Thermodynamic modelling is a potential tool for predicting alloy compositions suitable for thixoforming. Thixoformable alloys must have a wide melting range with some additional feature. Namely, the slope of the curve of the liquid fraction versus the temperature should be low at the liquid fraction value of 40%. The data from thermodynamic calculations might be also applied in the industrial thixoforming processes design. It is very helpful to find different thermal properties of alloys in order to simulate precisely the temperature distribution inside the formed materials. The thermodynamic calculations allow one to find the heat transfer coefficient, the specific heat value and the latent heat value. The purpose of the present paper is to provide examples of the numerical modelling of the thermodynamic properties for commercial, industrial Al alloys. All the calculations in the present work are performed using JMatPro software. The determination of the phase composition for multi-component alloys is originally based on the Gibbs energy minimisation. Furthermore, the conditions of the non-equilibrium solidification are determined using the Scheil-Gulliver equation. An additional advantage of the software used is the possibility of calculation of the formation conditions for metastable phases which have also an influence on the mechanical properties of the alloys.

Keywords: computer simulation, thermodynamic calculations, aluminium alloys, phase change, thixoforming, rheology

Procesy przetwórstwa metali w stanie stało-ciekłym są nową, sprawdzoną komercyjnie, metodą precyzyjnego kształtowania dużej ilości elementów. Przykładem takiej technologii jest formowanie tiksotropowe, właściwością którego jest specyficzne zachowanie formowanych stopów posiadających niedenndrytyczną mikrostrukturę w częściowo ciekłym stanie. Projektowanie procesów formowania w stanie stało-ciekłym wymaga użycia prawidłowych wartości własności termodynamicznych materiałów. Modelowanie termodynamiczne jest potencjalnym narzędziem opracowania składu chemicznego stopów odpowiednich dla formowania tiksotropowego. Tiksoformowalne stopy muszą posiadać szeroki zakres temperatur krzepnięcia. Ponadto, nachylenie krzywej ułamka fazy ciekłej w zależności od temperatury powinno być jak najmniejsze dla wartości 40% tego ułamka. Wyniki obliczeń termodynamicznych mogą mieć również zastosowanie w trakcie projektowania przemysłowych procesów formowania tiksotropowego. W szczególności symulacje rozkładu temperatury wewnątrz formowanego materiału wymagają znajomości wartości jego właściwości termo-fizycznych. Obliczenia termodynamiczne pozwalają, między innymi, wyznaczyć współczynnik wymiany ciepła, ciepło właściwe czy ciepło przemiany fazowej. Celem tej pracy jest przedstawienie przykładów zastosowania modelowania numerycznego własności termodynamicznych przemysłowych stopów aluminium. Wszystkie obliczenia zostały wykonane z wykorzystaniem oprogramowania JMatPro. Wyznaczenie składu fazowego dla wieloskładnikowych stopów zostało oparte na minimalizacji energii Gibbs'a. Ułamek fazy ciekłej w warunkach nierównowagowego krzepnięcia został wyznaczony w oparciu o równanie Scheil-Gulliver'a. Dodatkową zaletą wykorzystanego oprogramowania jest możliwość przewidywania warunków powstawania metastabilnych faz, które mają wpływ na właściwości mechaniczne stopów.

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1. Introduction

Thixoforming processes allow complicated shapes to be obtained in a single technological operation (near net shaping). These processes require the formed alloys to have a semi-solid state and a globular microstructure (solid metal spheroids in a liquid matrix). Different methods have been designed to achieve such a microstructure. Thixoforming processes can be carried out using different methods usually derived from forging and high pressure casting. Other advantages of this technology are that it results in a product with superior mechanical properties compared to classical casting, there are less deformation forces compared to classical metal-forming, and it allows deformation of alloys with a low degree of plasticity using forging technology.

It should be emphasised that such processes are carried out in non-isothermal conditions. Normally the temperature of the shaping tools are much lower than that of the formed alloys. In order to avoid solidification of the material before the completion of the shaping process a relatively high shear rate should be applied. Also, in such processes the alloys must have a wide melting range.

This paper concerns the selection of both cast and wrought aluminium alloys for semi-solid processes using thermodynamic calculations. Thixoformability is the term usually used to indicate the suitability of alloys for thixoforming. Selection of thixoformable alloys was based on identification of compositions and the effect of the alloying elements on the fraction liquid distribution during solidification. It is essential to select suitable alloys which meet the requirements of semi-solid processing. This requires analysis of the distribution of fraction liquid versus temperature, the temperature range for the fraction liquid from 30 to 50%, the fraction liquid sensitivity and also the solidification range of the alloys (see Fig. 1) [1, 2]. The optimum apparent viscosity in thixoforming processes occurs from 30 to 50% fraction liquid. In order to avoid large variations of this fraction with changes in temperature the fraction liquid sensitivity should be as low as possible. The sensitivity of 40% fraction liquid should be less than 0.025 K^{-1}. The temperature processing window for the fraction liquid from 30 to 50% should be relatively wide (greater than 15 K). Also, the temperature of the binary eutectic reaction should be reached between 30 and 50% liquid. Above this temperature fraction liquid sensitivity is low so the changes of this fraction are controllable. Another aspect which should be analysed during selection of proper alloys is the solidification interval, which should be of limited width to avoid excessive susceptibility to hot tearing. The latter requirements are not always met for all alloys. The possibility of an increase in age-hardening and improvement of the mechanical properties by precipitates formed during thermal treatment should also be taken into consideration.

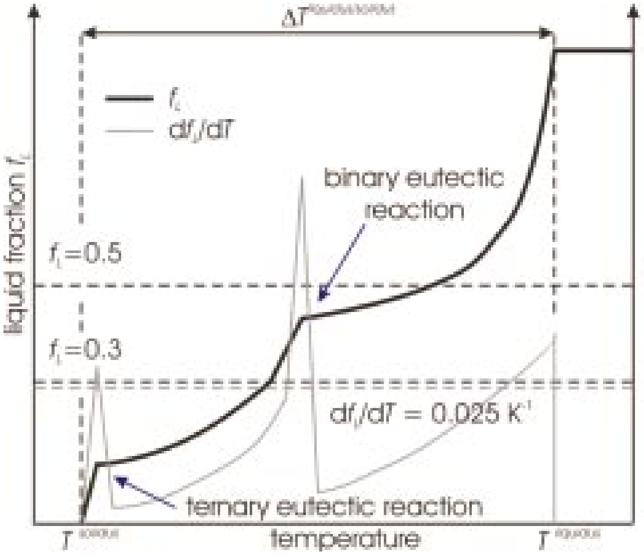

Fig. 1. Schematic diagram of the fraction liquid and the fraction liquid sensitivity distribution

Thixoforming is used commercially to mass produce automotive components, but only with conventional casting alloys such as A356 and A357, which for the most part are produced by MHD stirring. There is considerable interest in extending its application to higher performance wrought specification aluminium alloys such as the 2000, 6000, and 7000 series. The distribution of the fraction liquid (calculated using JMatPro software) of the most popular thixoformed cast aluminium alloys (A356, A357) and wrought aluminium alloys currently being tested for thixoforming (2014, 6082, 7010, 7050, 7075) is shown in Fig. 2.

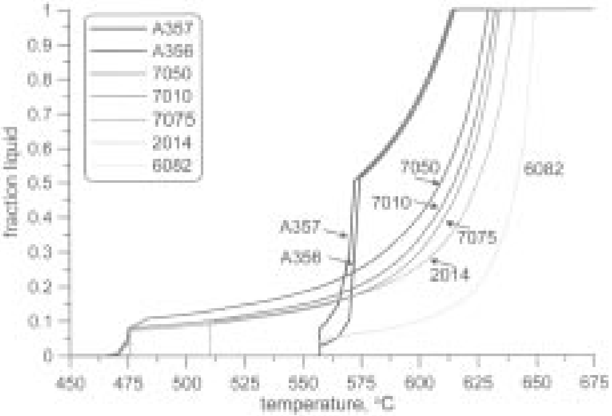

Fig. 2. Distribution of the fraction liquid of the most popular thixoformed aluminium alloys

This work examines the thixoformability of the above-mentioned alloys and the effect on thixoformability of adding copper, zinc and magnesium; analyses both the cast and the 7000 series Al-Zn-Mg-Cu aluminium alloys by means of thermodynamic calculations to identify the compositions likely to be most suitable; and finally describes the possibility of determining thermo-physical properties using JMatPro software for the finite element simulations of shaping.

2. Solidification modelling

The fraction liquid f_l and the fraction liquid sensitivity $\mathrm{d}f_l/\mathrm{d}T$, defined as the rate of change of the fraction liquid with temperature, are extremely important parameters for semi-solid forming. These parameters can be obtained experimentally, for example by differential scanning calorimetry, and predicted by thermodynamic modelling. When using experimental methods it is necessary to prepare the alloys in order to obtain samples. This would involve lengthy experimentation to analyse selected alloys. Thermodynamic modelling allows solidification parameters to be investigated without the need to prepare any material. Analysis of the solidification process of aluminium alloys was carried out using JMatPro software [3]. This software allows the calculation of the fraction liquid/temperature relationship using an analytical solution based on Scheil-Gulliver's equation for multicomponent systems [4]. Thermodynamic modelling also allows prediction of a number of critical thermo-physical properties for a variety of alloy types during solidification. Such calculations can be carried out extremely rapidly and used within FE packages which allow simulation of thixoforming processes.

For equilibrium solidification described by the level rule and with linear liquidus and solidus lines the composition of the solid C_s as a function of the fraction solid f_s transformed is given by:

$$C_s = \frac{kC_0}{f_s(k-1)+1}, \tag{1}$$

where k is the partition coefficient ($k = C_s/C_l$) and C_0 is the composition of the original liquid alloy. This can be re-arranged thus:

$$f_s = \left(\frac{1}{1-k}\right)\left(\frac{T_l - T}{T_s - T}\right), \tag{2}$$

where T_l and T_s are the equilibrium liquidus and solidus temperatures. A complementary limiting case for equilibrium solidification is to assume that solute diffusion in the solid phase is low enough to be considered negligible and that diffusion in the liquid is extremely rapid, rapid enough to assume that diffusion is complete. In this case Equation (1) can be re-written as

$$C_s = kC_0(1-f_s)^{k-1} \tag{3}$$

and Equation (2) as

$$f_s = 1 - \left(\frac{T_s - T}{T_s - T_l}\right)^{\left(\frac{1}{1-k}\right)}. \tag{4}$$

The treatment above is the traditional derivation of the Scheil-Gulliver equation but it has quite severe restrictions when applied to multicomponent alloys. It is not possible to derive this equation, using the same mathematical method, if the partition coefficient, k, is dependent on temperature and/or composition. The partition coefficient k can be usually constant. Its dependence on the temperature and/or composition does not essentially correct results of the calculations. Exceptionally, the partition coefficient has to be variable for some alloys, which have the complicated shape of the liquidus line, such as Al-Zn alloys. The solution of the Scheil equation with the variable partition coefficient is described by Krupkowski [5]. The Scheil-Gulliver equation is applicable to solidification which is characterized by rapid diffusion in the liquid phase and no diffusion in the solid phase. Further this equation cannot be used to predict the formation of intermetallics during solidification.

Using thermodynamic modelling all of the above disadvantages can be overcome. The approach which should be applied is based on an isothermal step process. As the temperature step size becomes small it provides results that are almost completely equivalent to that which would be obtained from continuous cooling.

The level rule and the Scheil model describe two extreme cases; equilibrium and non-equilibrium, non-diffusion solidification processes. These cases are abstract, impossible to achieve in reality. One can find some papers which take into consideration also the partial back-diffusion [6]. Using the model which describe this phenomenon allow to obtain more precisely results. However, the application of approach used in JMatPro software can be useful for design thixoforming processes. Thermodynamic calculations described in this paper concerns selection of the proper alloys. The application of the thermo-physical properties, obtained this way, also can be used in the numerical modelling of thixoforming processes. But it should be mentioned, that models used in the thermodynamic modelling do not take into consideration all phenomena proceeded in the solidified metal alloys during deformation and further investigation should be carried out.

3. Thixoformability of A356 cast aluminium alloy and A356 modified with added copper

Many feasibility studies have demonstrated that practically all the metallic alloys of major commercial interest can be thixoformed, but those that have the widest range of applications in the automotive field are the cast aluminium alloys. The most popular casting alloys A356 and A357 are now available on the market in the form of thixocasted billets ready to be formed. Conventional aluminium casting alloys have added silicon which ensures high fluidity. Such alloys have high corrosion resistance combined with a low coefficient of thermal expansion and good weldability.

The thixoformabilty of these alloys can be improved by adding copper. The effect of adding copper on the distribution of the fraction liquid of A356 alloy (Al-7Si-0.3Mg-xCu, wt%) is shown in Fig. 3. The addition of copper causes an increase in the temperature processing window for the fraction liquid range suitable for semi-solid processing. The exact solidification parameters of A356 alloy modified with added copper are given in Table 1. Addition of copper from 0 to 10 wt% causes the reduction of fraction liquid sensitivity at 0.4 fraction liquid from 0.08 to 0.01 K^{-1}, at which point the slope of the curves at 0.4 fraction liquid $(df_l/dT)_{fl=0.4}$ becomes less steep. The temperature working window between 0.3 and 0.5 fraction liquid $(\Delta T^{0.3/0.5})$ is enlarged from 4 to 25 K. Also, adding Cu to Al-Si alloys causes the formation of certain intermetallic compounds (fe. $CuAl_2$) which increase strength and heat treatability. However, the addition of copper also decreases castability. The compound $CuAl_2$ included in the ternary eutectic occurring during non-equilibrium solidification causes an increase in the solidification range compared to the narrow solidification interval (59 K) for normal A356 alloy. Most of the criteria described in Chapter 1, which determine thixoformability, were achieved by adding copper. The most important of these: the width of the temperature processing window and fraction liquid sensitivity allow for satisfactory semi-solid processing.

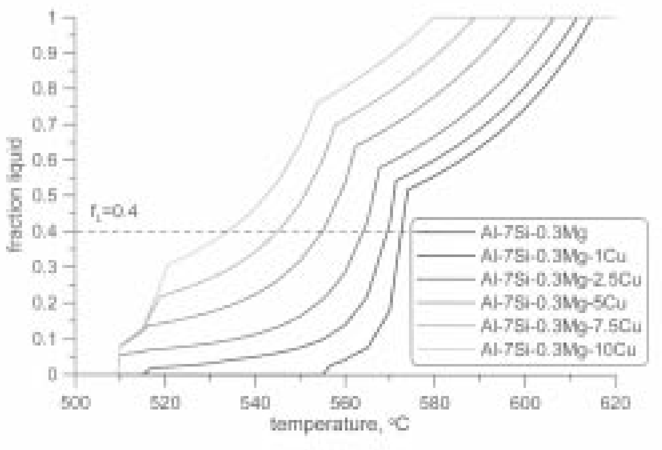

Fig. 3. Fraction liquid vs. temperature given by JMatPro for alloy A356 (Al-7Si-0.3Mg, wt%) and A356 modified with added Cu

TABLE 1

Solidification parameters given by JMatPro software for alloy A356 and alloy A356 modified with added copper (Al-7Si-0.3Mg-xCu, wt%)

Cu (wt%)	$T_{solidus}$ (°C)	$T_{liquidus}$ (°C)	$\Delta T^{solidus/liquidus}$ (K)	$(df_l/dT)_{fl=0.4}$ (K^{-1})	$\Delta T^{0.3/0.5}$ (K)
0.0	556	615	59	0.083	4
1.0	516	612	96	0.067	6
2.5	509	606	97	0.055	8
5.0	509	598	89	0.025	12
7.5	509	589	80	0.016	16
10.0	509	580	71	0.010	25

4. Thixoformability of 7000 series wrought aluminium alloy

The second part of the analysis concerned the thixoformabilty of high strength wrought aluminium alloys (Al-Zn-Mg-Cu). This analysis was based on the determination of the influence of Zn/(Mg+Cu) ratio and the Zn+Mg+Cu content on the solidification parameters constituting the thixoformability criteria described in Chapter 2. The effect of the Zn+Mg+Cu content on the solidification parameters estimated by JMatPro software is shown in Figure 4. The ratio Zn/(Mg+Cu), amounting to 1.5, was constant for each alloy. Figure 4 shows that when the Zn+Mg+Cu content is greater than 7 wt%, the liquid fraction sensitivity is relatively low (less than 0.015 K^{-1}) and the temperature processing window relatively wide (greater than 15 K). Otherwise, the alloys are not sufficiently thixoformable. The effect of the Zn/(Mg+Cu) ratio on the solidification parameters estimated by JMatPro software is shown in Figure 5. The Zn+Mg+Cu content of 9% was constant for each alloy. Figure 5 shows that when the Zn/(Mg+Cu) ratio is less than 2, the liquid fraction sensitivity is sufficiently low (less than 0.013 K^{-1}) and the temperature processing window relatively wide (greater than 15 K).

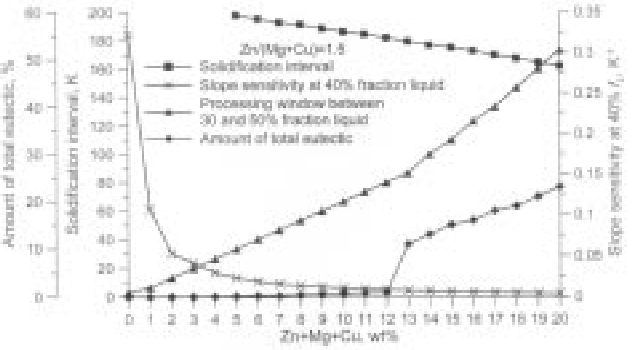

Fig. 4. The effect of (Zn+Mg+Cu) content on the solidification parameters estimated by JMatPro software for alloy Al-xCu-yMg-zZn (wt%) when z/(x+y) = 1.5

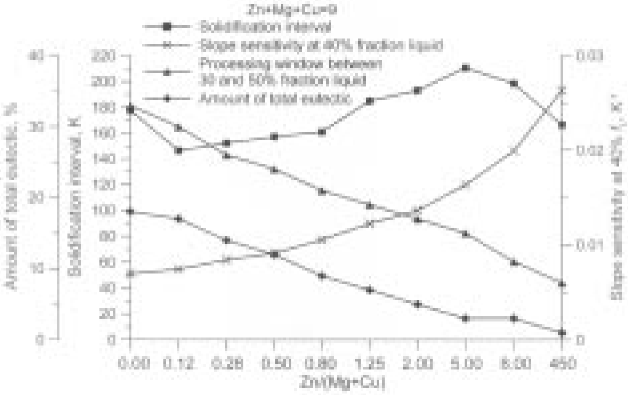

Fig. 5. The effect of (Zn/(Mg+Cu)) ratio on the solidification parameters estimated by JMatPro software for alloy Al-xCu-yMg-zZn (wt%) when x+y+z = 9

Otherwise, the alloys are not sufficiently thixoformable. The distributions of the liquid fraction, determined using the Scheil-Gulliver equation, for selected 7000 series aluminium alloys is shown in Figure 6 and 7. Figure 6 shows dependence on the Zn/(Mg+Cu) ratio, which has different value for each alloy. The value of this ratio for the 7030 alloy equals 5 and therefore this alloy is not good candidate for the semi-solid processes. Figure 7 shows dependence on the Zn+Mg+Cu content, which has different value for each alloy. The value of this sum for the 7116 alloy equals 6.7 and therefore this alloy is not good candidate for the semi-solid processes. Table 2 contains commercial alloys compositions in wt%, Zn/(Mg+Cu) ratios, Zn+Mg+Cu content, $(df_l/dT)_{fl=0.4}$ liquid fraction sensitivity and $\Delta T^{0.3/0.5}$ temperature range for 30–50% liquid fraction are shown. The values of the solidification parameters from this Table confirm the uselessness of 7116 and 7030 alloys for thixoforming processes. The 7001, 7050 and 7075 show the greatest degree of thixoformability with a temperature processing window above 20 K.

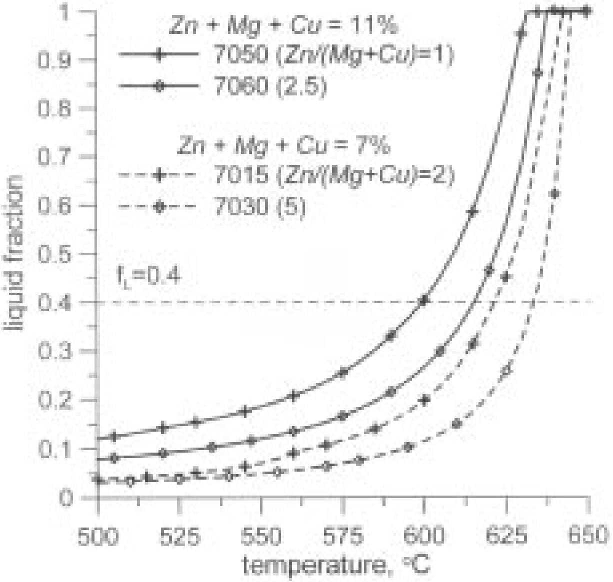

Fig. 6. The effect of Zn/(Mg+Cu) ratio on the distribution of the fraction liquid (Scheil-Gulliver equation) for selected 7xxx series aluminium alloys

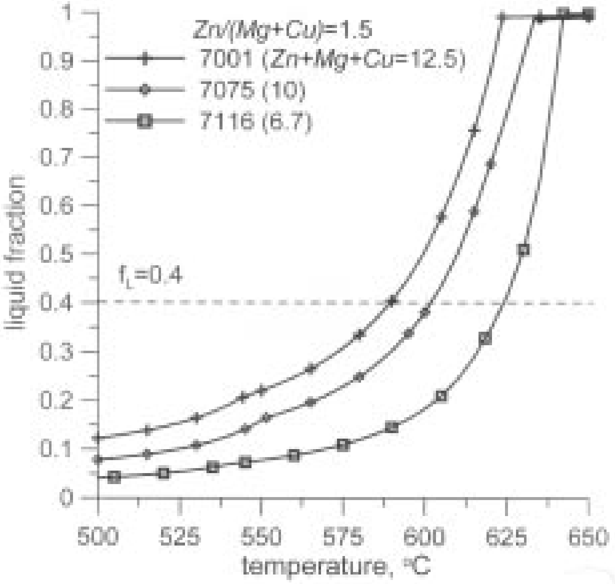

Fig. 7. The effect of (Zn+Mg+Cu) content on the distribution of the fraction liquid (Scheil-Gulliver equation) for selected 7xxx series aluminium alloys

TABLE 2

Commercial alloy compositions in wt%, Zn/(Mg+Cu) ratios, Zn+Mg+Cu content, $(\mathrm{d}f_l/\mathrm{d}T)_{fl=0.4}$ liquid fraction sensitivity and $\Delta T^{0.3/0.5}$ temperature range for 30–50% liquid fraction

Alloy	Si wt%	Fe wt%	Cu wt%	Mn wt%	Mg wt%	Zn wt%	Cr wt%	Zn+Mg+Cu wt%	Zn/(Mg+Cu) wt%	$(\mathrm{d}f_l/\mathrm{d}T)_{fl=0.4}$ (K^{-1})	$\Delta T^{0.3/0.5}$ (K)
7001	0.35	0.40	2.10	0.20	3.00	7.40	0.25	12.50	1.45	0.009	25
7050	0.12	0.15	2.60	0.10	2.60	5.70	0.04	10.90	1.10	0.010	25
7075	0.40	0.50	1.60	0.30	2.40	6.00	0.28	10.00	1.50	0.010	20
7060	0.01	0.01	1.80	0.01	1.30	7.50	0.15	10.60	2.42	0.013	17
7015	0.20	0.30	0.15	0.10	2.10	4.60	0.15	6.85	2.04	0.015	15
7116	0.15	0.30	1.10	0.05	1.40	4.20	–	6.70	1.68	0.026	10
7030	0.01	0.01	0.20	0.01	1.00	5.90	0.01	7.10	4.92	0.037	7

5. Application of thermodynamic calculations in numerical modelling of thixoforming processes

5.1. Physical simulations of thixoforming using a GLEEBLE thermomechanical simulator

A combination of physical and numerical simulations of metal-forming processes can be used effectively to examine the rheological properties of the materials. The shaping of the metal alloys in the semi-solid state requires special conditions, difficult to achieve in practice, related to the temperature range of the shaped alloys. As was mentioned in previous chapters, the temperature processing window is limited in width to a maximum of a few dozen K for some alloys. Achieving temperature heterogeneity requires suitable equipment. The Gleeble thermomechanical simulator is designed to carry out material tests in controlled strain conditions. Also, a protective atmosphere may be applied to avoid oxidation. An argon atmosphere was used in simulations. The Gleeble simulator was not originally equipped with suitable tools for analysing semi-solid processes. The main difficulties concern the resistance heating applied in this simulator. A special set-up had to be designed in order to control the temperature very precisely and obtain temperature homogeneity [7, 8]. This experimental set-up, which was used to test the aluminium specimens, is shown in Fig. 8. It is an adaptation of the simulator for material tests of light metal alloys. The single simulation consists of three stages: in the first stage the material is heated in a steel chamber. In the second stage the material is moved from the steel chamber to the mould by the piston. The third stage involves shaping the material inside the mould. The radial extrusion material test was used to analyse the rheology of aluminium alloys. Samples with initial radius and high equal 12 were extruded into the radial cavity (see Fig. 10).

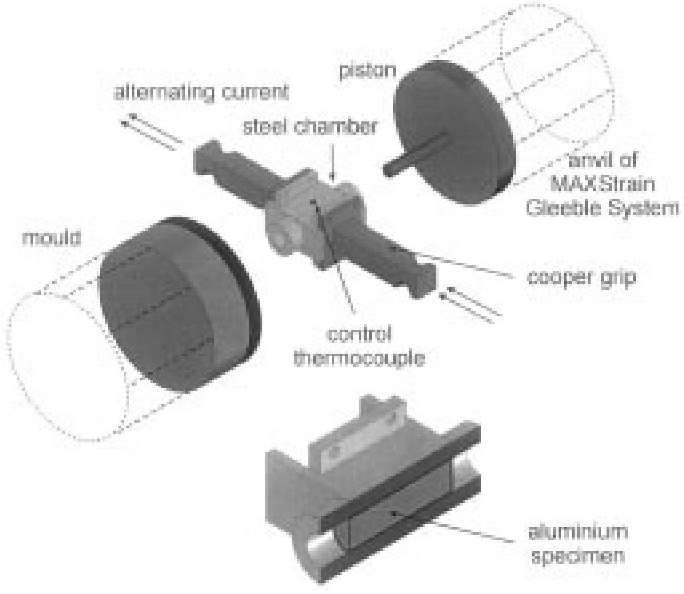

Fig. 8. The experimental set-up used to test the aluminium specimen

5.2. Numerical simulations of thixoforming supported by calculations of thermo-physical properties

Theoretical analysis was carried out with the aid of metalforming terminology [9]. Experiments described in previous Section were numerically simulated using the viscoplastic modified power law model (5) implemented in ADINA software. The finite element method was used to solve the thermal and mechanical equilibrium equations at each time step of the process. The rheological model of the material is described using power low model [10, 11]:

$$\tau = K\,(f_L)\cdot\dot{\gamma}^{m(f_L)}, \tag{5}$$

where: τ – the shear stress, K – the viscoplastic consistency, m – the strain rate sensitivity, $\dot{\gamma}$ – the shear strain rate. The apparent viscosity η_{app} which derives from Equation (5) can be expressed as:

$$\begin{aligned}\eta_{app}(\dot{\gamma}) &= K(f_L)(\dot{\gamma})^{m(f_L)-1} \ \text{ for } \dot{\gamma} \geqslant \dot{\gamma}_0 \\ \eta_{app}(\dot{\gamma}) &= K(f_L)(\dot{\gamma}_0)^{m(f_L)-1} \ \text{ for } \dot{\gamma} < \dot{\gamma}_0,\end{aligned} \tag{6}$$

where $\dot{\gamma}_c$ is the shear rate cut-off. The arbitrary Lagrange-Euler approach (ALE) is employed in ADINA, i.e. the velocity of the nodes of the mesh is not equal to the velocity of the material points. The main advantage of this approach is that the free surface is accurately tracked. The strain rate sensitivity m may be taken with following values:

- $m = 0.2$ for a hot solid state,
- $m = 1.0$ for a liquid state, which corresponds to pure Newtonian behaviour,
- $m \in (0.2; 1.0)$ for a semi-solid state.

The value of exponent m of around 0.2 means lack of liquid phase, and the value of exponent m equals 1.0 means lack of solid phase. Therefore the strain rate sensitivity allow to model the state of aggregation of the material.

The flow of material in the semi-solid state is very sensitive to temperature. This is why the distribution of the temperature should be determined very precisely. However, temperature distribution is particularly dependent on the phase change [12, 13]. Solidification is accompanied by the release of latent heat at the solid-liquid interface. The various methods differ in the way the latent heat release is handled and may be broadly classified as *front tracking methods* and *fixed grid methods*. Fixed grid methods treat both the solid and liquid regions as one continuous region and the phase boundary is never explicitly determined. These methods can be used for conventional alloys or an impure metals. One kind of fixed grid method is *the entalphy method* for which the following equation is introduced:

$$\rho \frac{\partial H}{\partial t} = \nabla \cdot (k \nabla T), \tag{7}$$

where: H – the enthalpy function, ρ – density, k – thermal conductivity, t – time. For the phase change occurring in an interval of temperatures between solidus T_s to liquidus T_l, the enthalpy function can be defined as follows:

$$H(T) = \int_{T_0}^{T_{sol}} c_p(T)\,\mathrm{d}T + \int_{T_{sol}}^{T} \left[\left(\frac{\mathrm{d}L}{\mathrm{d}T}\right) + c_p(T)\right] \mathrm{d}T, \tag{8}$$

where: T_{ref} – reference temperature below T_s, C_p – specific heat, L – the latent heat. During the phase change solidification shrinkage occurs, which can be defined as follows:

$$\alpha = \alpha_{th} + \frac{1}{3\Delta T} \Delta V_{Ph}, \tag{9}$$

where: α – the global expansion coefficient, α_{th} – the thermal expansion coefficient, ΔV_{Ph} – the relative volume change associated with the total liquid-solid transition.

All these models require correct thermo-physical properties (which can be calculated using JMatPro software). Some examples of such properties (included the liquid fraction, specific heat, enthalpy and latent heat) determined for 7075 alloy are shown in Fig. 9. An advantages of using correct values for these properties is that it allows a high degree of agreement between calculated and measured forces vs. the piston displacement to be achieved (see Fig. 10).

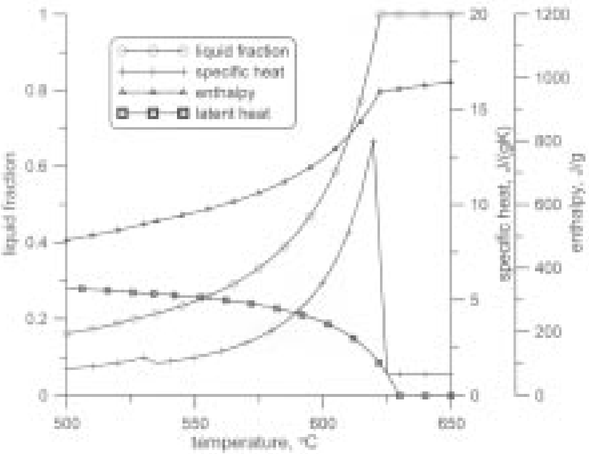

Fig. 9. The thermo-physical properties of 7075 alloy

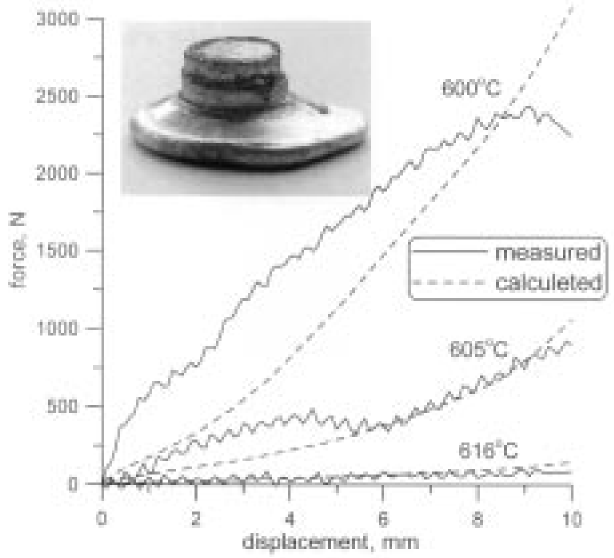

Fig. 10. Comparison of measured and calculated forces versus piston displacement for 7075 aluminium alloy. Photograph: extruded die forging

6. Discussion and conclusions

Thermodynamic modelling is a useful tool in the design of new alloys for thixoforming. The most important parameters which should be considered during selection of the proper alloys are the temperature range for the liquid fraction from 30 to 40% and the liquid fraction sensitivity to temperature changes at 40% fraction liquid. The chemical composition of 7000 series aluminium alloys should meet certain requirements: thixoformability should increase as the Zn/(Mg+Cu) ratio decreases and the sum of Zn+Mg+Cu increases. Optimum conditions for thixoforming should be obtained when Zn/(Mg+Cu) < 2 (in wt%) and Zn+Mg+Cu > 7wt%. Alloys with Zn+Mg+Cu content of less than 7wt% will be difficult to thixoform, even when the Zn/(Mg+Cu) ratio is very low.

Thermophysical properties of alloys calculated using JMatPro software can be used in numerical modelling of thixoforming processes.

The Norton-Hoff law allows a correct description of material in a semi-solid state to be obtained. This approach also allows calculation of the value of the technological parameters of the process e.g. piston forces. This single-phase viscoplastic model does not include many parameters, which is the main advantage of the model.

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