Aluminum properties, a model for calculating mechanical properties in AlSiMgFe-foundry alloys

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Abstract

A semi-empirical model named ALPROP has been developed for the calculation of tensile properties and hardness in AlSiMg(Fe) Foundry Alloys. With chemical composition, dendrite arm spacing (DAS) and heat treatment parameters as input the model calculates tensile properties and hardness for material in as cast, solid solution heat treated and in artificially aged condition. The model, which takes into consideration the relationship between the different input parameters and the link to basic metallurgical features, shows good agreement with experimental results. The ALPROP model has proved to be a useful tool for tailoring mechanical properties by correct choice of chemical composition and process parameters, for analysing consequences and identifying possible actions when having unintended process variations, identifying improvement potensials and for training of foundry staff.

Riassunto

Un modello semi-empirico denominato ALPROP è stato elaborato per il calcolo delle proprietà trazionali e della durezza delle leghe AlSiMg (Fe) di fonderia. Utilizzando quali parametri di ingresso la composizione chimica, l'intervallo del braccio dendritico (DAS) ed il trattamento termico, il modello calcola le proprietà trazionali e la durezza di un materiale nelle condizioni "as cast", trattato termicamente in soluzione solida, o artificialmente invecchiato. Il modello prende in considerazione il rapporto tra i parametri d'ingresso ed il collegamento con le caratteristiche metallurgiche di base. Vi è anche un buon accordo tra i risultati forniti dal modello e quelli sperimentali. Il modello ALPROP si è pure dimostrato essere utile come strumento per la regolazione delle proprietà meccaniche tramite la giusta scelta dei parametri della composizione chimica e del processo, per l'analisi delle conseguenze e l'individuazione delle azioni da intraprendere nel caso di varizioni del processo indesiderate, per l'identificazione delle possibilità di miglioramento e per la formazione del personale della fonderia.

INTRODUCTION

Hypoeutectic AlSiMg primary foundry alloys combines excellent castability with the possibility of obtaining castings with high ductility, fracture thoughness and fatigue properties. In addition, moderate to high strength can be achieved by applying heat treatment to the castings. These properties makes the alloys suited for demanding applications within the automotive segment. Products as wheel rims, master brake cylinders and structural parts (f.ex. sub frames) are made from AlSiMg primary foundry alloys.

Mechanical properties are linked to the microstructure in the material which again is determined by chemical composition (trace elements, alloying elements), heat treatment parameters (time, temperature combinations) and casting conditions (solidification rate, temperature gradients, casting defect). With so many parameters influencing the microstructure and mechanical properties both individually and coupled, it is difficult to predict precisely the effect of a change in one or several parameters on the product properties. The best way of achieving this is to evaluate and systemise available information into a computer program, also taking into consideration the relationships between the different parameters and the link to basic metallurgical understanding of what is behind the effects observed. These ideas were the origin to the development of the AlProp model, and the motivation was to establish a tool to be used in technical support to Hydro Aluminium's Foundry Alloy customers.

DESCRIPTION OF THE MODEL

Model concept

AlProp consists of a set of equations relating microstructure parameters to chemical composition, secondary dendrite arm spacing (DAS) and the heat treatment parameters. Another set of equations link the tensile properties to the microstructure parameters. The equations are based on physical and metallurgical conceptions on the formation of the microstructure and how it determines the mechanical properties. Fundamental equations are, however, not very applicable to complex multi-phase systems such as AlSiMgFeSr, and the mathematical descriptions are therefore motivated by the need of reproducing experimental data. The present version of the AlProp model is microstructure-controlled, i.e. the effect of porosity and inclusions on the mechanical properties is not calculated.

Input and output

The calculations of mechanical properties are based on the following **input** parameters:

- Composition, i.e. Si (5-12 wt%), Mg (0.01-0.9 wt%), Fe (0.01-0.8 wt%) and Sr (0-500 ppm weight)
- The secondary dendrite arm spacing (10-150 μm)
- The solid solution heat treatment temperature (500-550°C) and time
- The intermediate room temperature time before artificial age hardening (0.1-200 hrs)
- The time and temperature (150-200°C) for a one – or two step artificial age hardening treatment.

Output is as follows:

i) Microstructure parameters after solidification and changes in them during solid solution heat treatment:

- Solid solubility of Mg and Si
- Fraction of eutectic structure
- The size and shape of the Si-particles (as observed in 2 dimensions)
- The fraction of other constituents, such as the β-AlFeSi (Al_5FeSi), Mg_2Si and π-AlMgFeSi ($Al_{18}Si_{10}Mg_7Fe_2$) [1]

ii) Yield strength, ultimate tensile strength, total elongation, the quality index (function of tensile properties) and Vickers hardness for the three conditions:

- as cast
- after solid solution heat treatment and prescribed room temperature storage time
- after artificial age hardening including a two-step process.

The Software

AlProp is written in Borland Turbo Pascal for Windows 3.11, but runs perfectly with Windows 95 and Windows NT. Input can be fixed, specified with one variable or even specified with one variable and two different values of a second parameter. The results are presented in tables and graphs with options for specifying the validity range of the axis and the density of calculation points. AlProp offers printing directly from the program or from spreadsheets reading a result file generated by the program.

Calculation of mechanical properties

Mechanical properties as cast

In AlProp yield stress, YS, of the eutectic fraction and the pre-eutectic fraction is calculated separately and combined with a simple law of mixture to obtain the final yield stress. While the pre-eutectic fraction is only a function of Mg (closely related to Mg in solid solution), the eutectic part is also a function of the fibrousity of the Si-particles. A fibrous structure reveals a higher resistance to yielding, as shown by [2] and [3]. We have observed a significant increase in strength

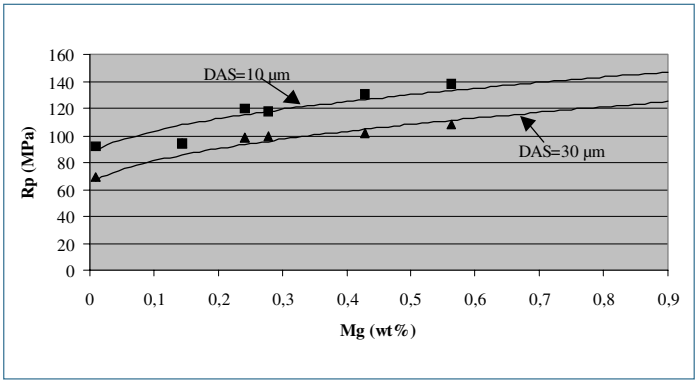

Fig. 1: Calculated as cast yield strength in AlSi7Fe0.1Mgx. Squares are experimental results from DC-cast material (DAS= 10 μm) and triangles from gravity die cast plates (DAS = 30 μm)

by increasing cooling rate, and a term including DAS has therefore also been included. Fig. 1 gives an example of calculated and measured yield stresses.

The tensile test itself with strain hardening, local necking and local deformation before final fracture is too complicated to model, especially for a complex structure as found in commercial AlSi-alloy. We have therefore developed an empirical expression for the total elongation in a tensile test (A_5-type geometry) based on the following concept:

The **total elongation A** decreases with:

- increasing fraction of eutectic structure (increasing Si)

- increasing Mg in solid solution increasing average area of Si-particles (function of Sr and DAS)
- increasing maximum length of Si-particles (function of Sr and DAS)
- decreasing average shape factor (function of Sr and DAS)
- increasing fraction of β-AlFeSi.

The maximum length of Si-particles and the fraction of β-AlFeSi is combined in one parameter so that the detrimental effect of Fe becomes relatively more important when the structure is modified.

Despite the fact that so many parameters are included, an additional DAS-adjustment proved necessary. The reason is that by decreasing DAS all the size parameters are reduced and the total elongation increases. However, the yield stress also increases as DAS is lowered, meaning that the elongation improves less than calculated from the particle size parameters alone.

The uniform part of the total elongation, A_u, is expressed by the following empirical equation:

$$A_u = A\text{-}0.03*A^{1.5} \quad (1)$$

The equation simply expresses that the post-uniform elongation constitutes a relatively larger part of the total elongation when the total elongation increases.

Knowing the uniform elongation, the ultimate tensile stress UTS can be calculated if the strain hardening of the tensile sample is known. AlProp applies a Ludvig stress-strain law for this purpose:

$$UTS = YS + K*\varepsilon_u^{\,n} \quad (2)$$

where

$$K = (250 + 100*Mg)e^{3.5/DAS} \quad (3)$$

$$\varepsilon_u = \ln(1+A_u/100) \quad (4)$$

$$n = 0.5 \quad (5)$$

The equation expresses that the strain hardening increases with increasing Mg and decreasing DAS. The value 0.5 is prescribed as a typical value for n in aluminium alloys when Ludvigs law is written as in eq. 2.

Vickers hardness HV is expressed by the same stress-strain law, making the assumption that a hardness indentation in average causes a true strain of 0.08. The proportionality factor this strain, between the stress and the hardness is 3:

$$HV = 1/3(YS+K*0.08^n) \quad (6)$$

Mechanical Properties in solution treated condition (T4)

The drop in the yield stress which is realized after solution treatment of A1SiMg foundry alloys is calculated by assuming a gradual decrease of the yield stress of the eutectic fraction in accordance with the calculation of the particle break-up and spherodization. The room temperature aging effect is calculated on an empirical basis.

The total elongation is represented by a complex formulae. It reflects that the improvement in the elongation compared to the as cast condition is less for the modified structure and also less when Fe is high. The p-AlFeSi morphology (large platelets) is relatively stable. Therefore, the total elongation in T4 will be increasingly dependent on the Fe content, and less dependant of the eutectic structure, as the Fe level increases. The reduction in total elongation with room temperature aging is also calculated on an empirical basis.

The ultimate tensile stress is calculated as explained in eq.2-5, but with a slightly higher value for K when Mg is high, because strain hardening during the tensile test is promoted by elements in solid solution.

The age hardening model

The concept of Shercliff and Ashby [4] was applied as a starting point for constructing age hardening curves. The model has a physical basis in the sense that the strength is built up of an intrinsic stress (the yield stress of the AlSiFe-alloy without Mg), a solid solution term that gradually decreases during aging, and an aging term that develops. In AlProp the T4-strength corresponds to the sum of the two first factors plus the effect of room temperature cold aging. The aging term is calculated on the basis of a metastable solvus at the aging temperature, giving the amount that can precipitate, and a precipitate coarsening model. The strength contribution from particles pinning dislocations (Orowan-mechanism) and from cutting the particles (Fridel-mechanism) reach a maximum at a certain particle size corresponding to the peak of the aging curve. The model does not distinguish between the different precipitate stages, and is in that sense incomplete. The important point, however, is that it offers a semi-physical mathematical description that can be further extended. In its original form the shape of the curve is fixed, i.e. only the peak level is adjusted. In our version of the model the shape is dependent on the Mg content, the room temperature aging time and the solid solution heat treatment temperature.

The model by Shercliff and Ashby applies a temperature compensated time parameter. This takes into account that the temperature may vary during the heat treatment. This has been utilized in order to model a two-step aging process, especially suitable for calculating the effect of a high temperature lacquering treatment following the artificial aging heat treatment.

The effect of room temperature storage on the T6-strength has been discussed by several authors, [5], [6], [7]. Most authors seem to agree that the T6-strength drops with in-

creasing room temperature storage for high M2Si levels, while an opposite effect can be found for low Mg2Si. [6] suggests that excess Si reduces the detrimental effect on T6 strength from intermediate room temperature storage. Our results are shown in fig.2. The figures show the importance of measuring the whole aging curve. It is quite clear that room temperature storage delays the aging response, and in the under-aged regime, room temperature storage will have a strength reducing effect. With a prolonged aging time (over-aging) the conclusion is the opposite. However, by ensuring a sufficient aging time, the detrimental effect of intermediate room temperature aging is almost zero.

The total elongation has a minimum for the peak situation, and the evolution of the total elongation with age hardening time is similar to that of the yield stress, but with an opposite sign. The effect of Mg is obviously strong, and also a combined effect of Fe, Si, Mg and DAS compared to the solid solution heat-treated condition is included in order to reproduce experimental results.

The ultimate tensile strength is again modeled as in eq.2-5, but with a slightly lower value for K than in the solid solution heat-treated condition. This is due to the fact that age hardened samples work harden less during the tensile test.

VERIFICATION AND USE OF THE MODEL

Model calculations have been compared with literature data. The difference between results from different sources makes the comparison difficult but the overall conclusion is that the model predicts the tensile properties fairly good. When comparing calculations with DC cast material, which is considered to be almost free of defects, we find that the calculations are in very good agreement with measurements.

The model has been utilized by Hydro Aluminium in technical support activities to foundry alloy customers. In particular, the use of the model for tailoring of properties by correct choice of Mg content and heat treatment conditions has proved to be successful.

Further, use of the model to reduce heat treatment times (reduced cost, increased productivity) without reducing the material properties has proved valuable. In two cases, the calculations showed the potential for a fifty percent reduction of the heat treatment time a 50% reduction of the without affecting properties and the implementation of the new time/temperature combinations proved successful.

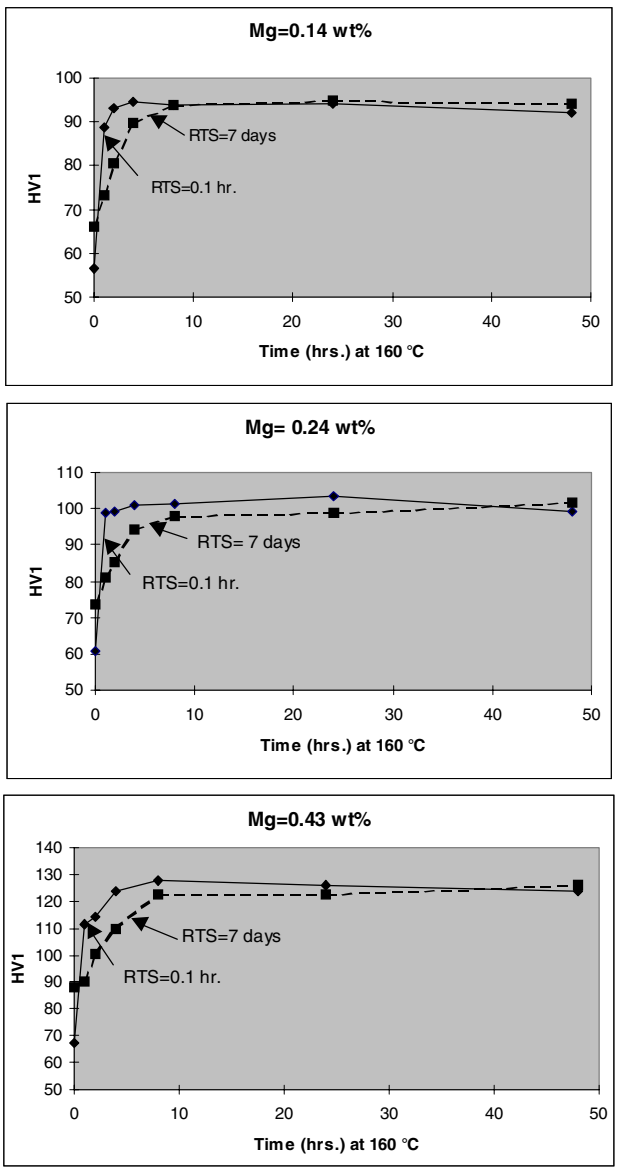

Fig.2: The effect of intermediate Room Temperature Storage time on Vickers hardness after age hardening at 160 °C

CONCLUSIONS

A model for calculating microstructure parameters, tensile properties and hardness of AlSiMg(Fe,Sr) foundry alloys has been developed. The equations used in the model are based upon physical and metallurgical conceptions on how microstructure is formed and how it determines the mechanical properties. Evaluation of the model reveals that it reproduces the available experimental data satisfactorily, and use of the model in technical support to foundry alloy customers have proved to be valuable.

Typical applications for the model is:

- tailor mechanical properties for castings by correct choice

of chemical composition and process parameters (heat treatment, casting conditions etc.)
- study the effect of different parameters on mechanical properties in order to:
  - analyze consequences of process variations (out of chemical specifications, variations in heat treatment conditions etc.)
  - identify possible actions when having process variations
  - identify improvement potentials
- training of foundry people, illustrate the effect of the different parameters on the product properties.

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