Development of a model for the prediction of mechanical properties for Al-Si-Mg castings

C. Ransenigo, M. Tocci, C. Viscardi, M. Serafini, A. Pola

A356 alloy is widely used to produce structural components by means of Low Pressure Die Casting (LPDC) process. Generally, a T6 heat treatment (solution, quenching and aging treatment) is carried out to improve the strength of the casting. Nowadays, software simulation of casting processes and solidification phenomena is a common practice for designing sound components even if mechanical strength values and their correlation with microstructure parameters are not given. However, the possibility to predict material behaviour before producing the castings would represent an additional precious tool for exploiting material properties. In the present study, a model for the estimation of tensile as-cast properties based on casting simulation was validated on a 22'' wheel obtained by LPDC. Microstructural and mechanical properties were investigated on the component both in as-cast and T6 condition. First, areas with different thicknesses and cooling conditions were analysed and secondary dendrite arm spacing (SDAS) measurements were carried out. Subsequently, tensile tests were performed on specimens from rim and spokes. Experimental data were used to verify the reliability of simulation results and to validate the as-cast model. Based on additional information provided by simulation software and experimental data, a mathematical model to predict the mechanical properties after T6 heat treatment was also proposed.

KEYWORDS: ALUMINUM, HEAT TREATMENT, SIMULATION, MODEL, CASTING;

NTRODUCTION

A356 is an aluminum casting alloy widely used because of its good castability, corrosion resistance and mechanical properties, in particular high strength-to-weight ratio, which make it suitable for various applications in the automotive industry [1]. In order to allow its use in structural application, generally a T6 heat treatment is carried out to further increase the strength of the castings [2]. Nowadays the quality of castings is constantly improving, also thanks to casting simulation software that provide results in terms of microstructure, defects like shrinkage porosity, solidification time, fraction solid and residual stresses [3] by modelling both mold filling and solidification phenomena. For instance, Sadeghi et al. [4] used simulation to predict fluid flow and solidification steps of the castings while Aloe et al. [5] focused their attention on the development of numerical tools to successfully predict stresses, microstructures and defects. Commercial casting software are not able to provide mechanical

C. Ransenigo, M. Tocci, A. Pola
Department of Mechanical and Industrial Engineering,
University of Brescia, via Branze 38, 25123, Brescia, Italy

Cristian Viscardi
Ecotre Valente srl, Via S. Orsola 145, 25135, Brescia, Italy

Marco Serafini
Maxion Wheels Italia srl, Via Roma 20, 25020, Dello (Bs), Italy

strength values before and after heat treatment. However, the possibility to predict the material behavior would represent a precious tool for exploiting material properties and simplifying production processes.

The aim of the work is to develop a mathematical model to successfully predict the local mechanical strength of the casting from the main microstructural parameters. In particular, specific equations to predict yield strength and ultimate tensile strength for the as-cast and T6 conditions were studied using the commercial software ProCAST®. First, microstructural and mechanical properties were investigated on a 22'' wheel obtained by LPDC process both in as-cast and T6 conditions. In parallel, using casting and geometrical parameters given by the foundry, a complete simulation was set up and a predictive model for as-cast condition was developed by exploiting the results. Experimental data were used for two main reasons: first, microstructural properties were used to verify the reliability of results from the casting simulation and then the validation of the predictive models for as-cast condition was carried out based on experimental tensile properties. Finally, a T6 model was proposed by extending the as-cast model previously validated.

EXPERIMENTAL PROCEDURE

The experimental tests were performed on two 22'' wheels obtained by LPDC using A356 alloy, one in as-cast condition, the other one after T6 treatment. The T6 heat treatment performed by the foundry consisted of solution treatment at 530 °C, quenching and then aging at 146 °C for 3 hours. A preliminary analysis was carried out in different positions of the as-cast wheel in order to analyze the influence of geometry and cooling rate on microstructure and to identify relevant sections for further characterization.

Five samples from the main spoke (letter A) and three from the minor one (letter B) were taken from the as-cast component in order to investigate different thicknesses: A1 and B1 from the rim, A2 at the root of the spoke, A3, A4, B3, B4 from the spokes and A5 close to the hub (Fig. 1). Fewer samples were examined on the second spoke because, after a preliminary analysis on the main one, it was found that they described the evolution of SDAS through the entire wheel in the most representative way.

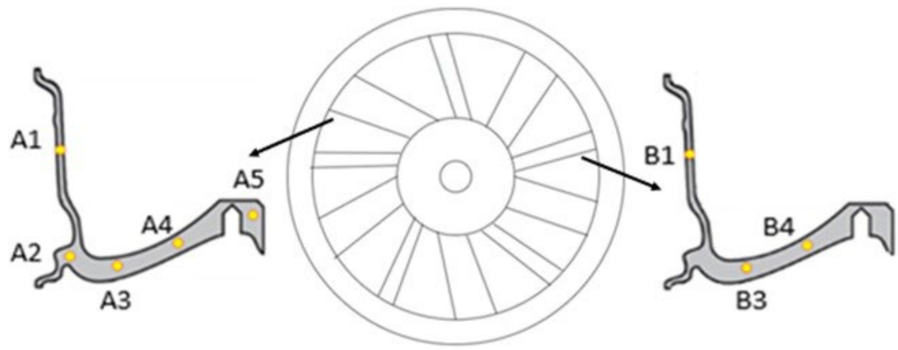

Fig.1 - Schematic representation of samples drawn from the two different spokes. For confidentiality reasons, the real wheel cannot be shown so a schematic representation is given.

The microstructure of the as-cast samples was observed via optical microscope Leica DMI 5000M after metallographic samples preparation. Average SDAS values were obtained for each sample using the linear intercept method. Several measurements were performed in order to obtain reliable mean values. Brinell hardness was measured on the as-cast and on the T6 samples in order to verify the increased resistance due to heat-treatment. More than 25 hardness tests were carried out with a load of 613 N and holding time of 15 seconds. Tensile tests were performed on cylindrical specimens with gauge length of 25 mm and average gauge diameter of 5 mm machined from the as-cast and T6 wheels. Samples position was chosen according to results from previous characterization: 3 coming from the rim (A1), 3 from the main spoke (A3) and 3 from the minor one (B3) for both the as cast and T6 component. An Instron 3369 testing machine with a load cell of 50 kN was used and a cross head speed of 1 mm/min was applied in the elastic field, while it was increased to 2 mm/min in the plastic field.

In parallel, using casting and geometrical parameters given by the foundry, a casting simulation was set up using a software widely used by foundries: ProCAST®. Subsequently, values of SDAS coming from the simulation were compared to experimental data in order to guarantee the reliability of simulation results. Based on information provided by simulation software, a mathematical model to predict yield strength and ultimate tensile strength for as-cast conditions was developed and validated using the experimental results coming from tensile tests, as described in the following section. A first predictive model for mechanical properties after heat treatment was also proposed.

RESULTS

Microstructural analysis

Microstructure of each as-cast sample, observed by optical microscope, is reported in Fig 2. A356 is a hypoeutectic aluminum-silicon casting alloy characterized by a primary dendritic phase, α-Al solid solution, and a eutectic mixture of aluminum and silicon, as indicated in the central in-set in Fig. 2. Intermetallic compounds, such as Fe-rich intermetallics, were seldom observed. As expected, a finer microstructure can be found at the rim, while it becomes coarser in the spoke and hub because of the reduction of cooling rate due to the increase of thicknesses. Analogous micrographs for the minor spoke and the T6 samples are not shown for brevity sake.

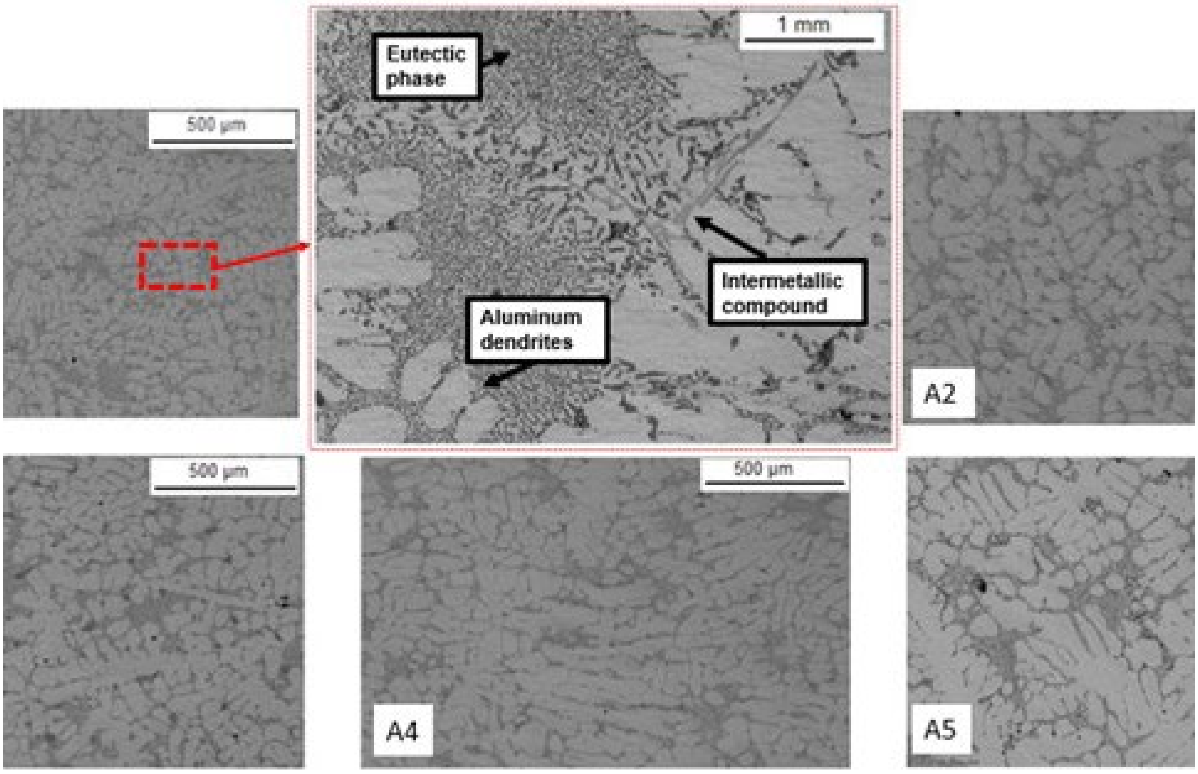

Fig.2 - Microstructure of each as cast sample. The central in-set shows the main microstructural constituents.

Simulation results

Simulation results in terms of microstructure, shrinkage porosity, solidification time, fraction solid and cooling rates are usually provided by the software. Among these, SDAS and level of shrinkage porosity were used in the present study. First, the values of SDAS coming from simulation were compared to experimental data and summarized in Tab. 1. The good agreement between them showed the reliability of simulation results and allowed them to be used in the development of the predictive models. Shrinkage porosity appears in one of the predictive models since it is known to affect the quality of the product and, consequently, its mechanical performances especially for those casting used in high-level request components [6]. Simulation values are reported in Tab.1.

Tab.1 - Simulation data and experimental values of SDAS and level of shrinkage porosity.

	A1	A2	A3	A4	A5	B1	B3	B4
Simulation SDAS [µm]	30	43	48	54	55	30.5	46	55
Experimental SDAS [µm]	31 ± 5	45 ± 6	48 ± 6	49 ± 6	59 ± 8	28 ± 3	45 ± 5	54 ± 5
Shrinkage porosity [-]	0.058	0.01	0.015	0.14	0.02	0.03	0.01	0.02

Tensile tests

Values of yield strength, ultimate tensile strength and elongation both in as-cast and T6 conditions are shown in Fig. 3.

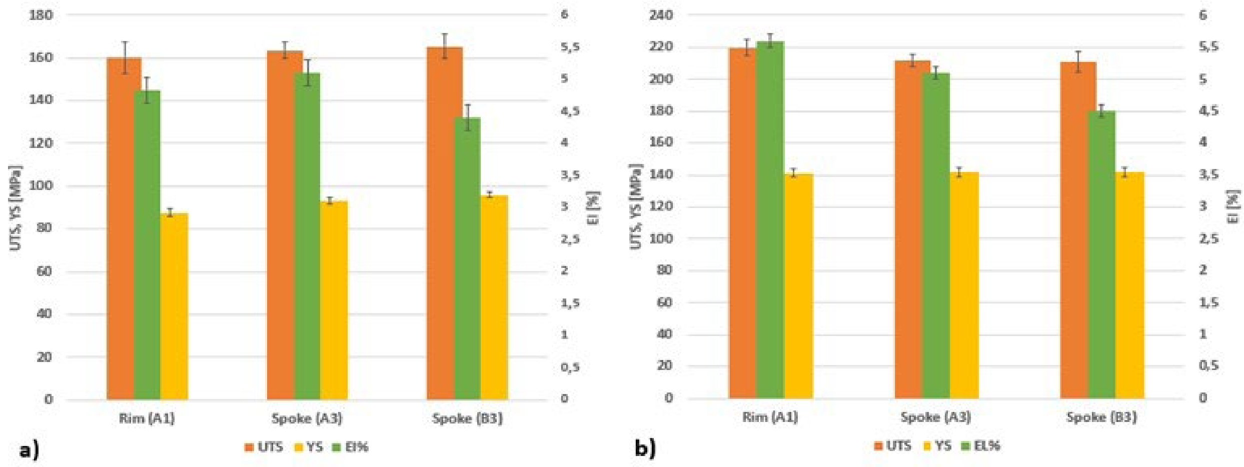

Fig.3 - Tensile properties from as-cast (a) and T6 (b) wheels.

For as cast condition, a uniform distribution of mechanical properties is displayed except for a slight reduction of elongation for the minor spoke (B3). No direct correlation between SDAS and tensile properties can be observed, suggesting that this point deserves to be better explored.

After T6, as expected, there is a marked increase of YS and UTS while elongation rises in a less remarkable way.

YIELD STRENGTH MODEL

As reported in literature [7], yield strength is mainly affected by microstructure following this general equation:

$$YS = A - B * ln\, ln\, (SDAS) \quad (1)$$

Simulation software provides YS values for as-cast conditions, obtained from interpolation of experimental data corresponding to different cooling rates, and SDAS values, which came from the casting simulation previously set up. Using YS and SDAS values provided by the software, unknown elements (A, B) of the general equation (1) were found. YS as well as SDAS values from three different positions were used (A1, A3, B3). Finally, an equation to predict the local tensile property was developed for the as-cast condition:

$$YS = 31.6 + 16.4 * ln\, ln\, (SDAS) \quad (2)$$

Tensile tests were used to validate the predictive model for as-cast condition (Tab.2): YS values coming from the application of the equation (2) are sufficiently close to the experimental ones. A comparison between predicted and experimental values showed that the mean error in the property prediction was about 2% of the actual measured value. The validation of this model ensured the possibility to implement the equation into the software in order to obtain reliable values of YS in any position of the casting, characterized by different thicknesses and solidification conditions, without performing any tensile tests. The simplicity of the equation is positive for its use at industrial level.

Tab.2 - Validation of as cast model.

	YS from the model [MPa]	Experimental YS [MPa]
A1	86.9	87.7 ± 2.1
A3	94.8	92.8 ± 1.9
B3	94.6	96 ± 1.4

A model for the estimation of YS for T6 condition was also developed, based on SDAS values, as an extension of the as cast model previously validated. Coefficients were defined following the same procedure as the as cast condition by exploiting experimental values of YS coming from tensile tests. The following equation is proposed:

$$YS = 135.6 + 1.67 * ln\, ln\, (SDAS) \quad (3)$$

ULTIMATE TENSILE STRENGTH MODEL

After a study of literature [8], it was found that Ludwig model represents the most reliable equation to predict UTS:

$$UTS = YS + K * \varepsilon^{\alpha} \quad (4)$$

where K is a function of SDAS while ε depends on tensile parameters. However, also casting defects, such as porosity level, are known to affect tensile strength, while they are not considered in Ludwig model. As expecting, after analyzing the correlation between the level of casting defects given by the software and UTS values, it was found that the higher the shrinkage porosity, the lower the mechanical strength value. Therefore, also the level of shrinkage porosities was taken into account for a more accurate estimation of UTS values. The possibility to analyze the strength reduction due to casting defects would represent an additional precious tool for predicting how solidification phenomena can affect material properties. The level of casting defects, together with the other input variables of equation, came from simulation results. A model to predict UTS both for as-cast and T6 conditions was developed:

$$UTS = YS * (1 - 0.5 * \%SHR.POROSITY) + \left(280 * 3 * e^{\frac{3.5}{SDAS}}\right) * \left(ln\, ln\, \left(1 + \frac{El\%}{100}\right)\right)^{0.5} \quad (5)$$

It is revealed that predictions from Eq. 5 are consistent with the experimental measurements of this property, thus the validation of the as-cast model is achieved (Tab. 3). In fact, the maximum error between the predicted UTS values and the experimental ones was about 5 MPa, which is lower than the experimental standard deviation. Thus, the validity of this metallurgical model is demonstrated. In this study, the most innovative contribution lies in the development of a new predictive model characterized by the appearance of shrinkage porosity. T6 model was developed by extending the as-cast model previously validated and by exploiting experimental results coming from tensile tests.

Tab.3 - Validation of as cast model.

	UTS from the model [MPa]	Experimental UTS [MPa]
A1	159.2	160.4 ± 7.3
A3	168.1	163.6 ± 6.1
B3	163.3	165.5 ± 5.9

CONCLUSIONS

In this study, a mathematical model to predict tensile behavior of A356 both for as-cast and T6 conditions as a function of microstructural parameters is proposed.

First, the yield strength was found to depend on SDAS and experimental values ensured the validation of the model for the as-cast condition. The same model was extended to predict the material behavior after heat treatment and new coefficients were found.

The ultimate tensile strength of the alloy was found to depend on SDAS, defects content and tensile parameters. After the validation of this model for the as-cast conditions, a new predictive equation was developed also for T6 conditions by exploiting experimental values. The two equations result to be the same since the difference lies in the value of each variable involved.

The good results obtained suggest that the proposed models could be integrated in the casting simulation software to obtain the local distribution of mechanical properties to be used during the re-design step of a new component. In this way, a reduction of thicknesses, where possible, can be achieved, and the always more restricted criteria for the lightening of vehicles can be met.

REFERENCES

[1] Kaufman J. G., Rooy E. L. Aluminium alloy castings, Properties, Processes and applications, ASM International; 2004.
[2] Morri A. Correlations among microstructure, effect of thermal exposure and mechanical properties, in heat treated Al-Si-Mg and Al-Cu aluminium alloys. 2012; 1-2.
[3] Abdullin A. D. New Capabilities of the ProCAST 2017 Software in Simulating Casting Processes. Metallurgist volume 61. 2017;433–438.
[4] Ravi, B. Computer aided design and analysis for zero defects. International Conference on Aluminum. 2000; 1-6.
[5] Aloe M., Lefebvre D., Mackenbrock A., Sholopurwalla A., Scott A. Advanced casting simulations. ESI Group, paper 30.
[6] Chudasama B. J. Solidification Analysis and Optimization Using Pro-Cast. International Journal of Research in Modern Engineering and Emerging Technology, Vol. 1, Issue: 4. 2013
[7] Shabani M. O., Mazaheri A. Prediction of Mechanical Properties of Cast A356 Alloy as a function of microstructure and cooling rate. Archives of Metallurgy and Materials, 2011; volume 56, issue 3.
[8] Brusethaug S., Langsrud Y. Aluminum properties, a model for calculating mechanical properties in AlSiMgFe-foundry alloys. Metallurgical Science and Technology, Volume 18; 2000.