Influence of Impurities and Gassing on the Tensile Properties of 2xx Sand Cast Al - Cu Alloys

Franco Chiesa[1], David Levasseur[2], Gheorghe Marin[3] and Bernard Duchesne[4]
1. Chief scientist
2. Project manager
3. General manager
Centre de métallurgie du Québec, Trois-Rivières, Québec
REGAL Aluminium Research Centre
4. Professor
Collège de Trois-Rivières, Trois-Rivières, Québec
Corresponding author: franco.chiesa@cegeptr.qc.ca

Abstract

Alloys A2xx (AlCu4) are the strongest aluminum casting alloys with tensile properties approaching those of ferritic ductile iron. These alloys are normally degassed before pouring but regassing of the melt might take place during handling. Also, returns used in the charge will cause an increase in impurity content (Fe, Si) and a consequent downgrading of alloy A206 to the 204 grade. In order to assess the effect of gassing on the tensile properties, well fed step castings, 6 mm, 13 mm and 25 mm in thickness were poured with degassed high purity A206 alloy and degassed and gassed alloy 204; the tensile properties for the three conditions were measured in the T4 and T7 tempers. The subsequent metallurgical study included metallographic analyses, grain size and microporosity measurements. The detrimental effect of tramp elements and gassing could be quantified by comparing the tensile properties of the alloys investigated. The drop in tensile strength observed was found to be more pronounced in the T7 tempers than in the T4 condition.

Keywords: Aluminium-copper alloys; sand casting; heat treatment; tensile properties.

1. Introduction

Since the take-off of the aluminum castings usage in the ‘70ies, the bulk of structural castings have been produced in Al-Si-Mg alloys (A356, 357) whether poured in sand or permanent mold. On the other hand, in spite of their “textbook” outstanding mechanical properties, aluminium-copper alloys of the 2xx series are still seldom used; the reason invoked is their susceptibility to hot tearing [1], the segregation of copper [2], and their sensitivity to stress corrosion cracking [3] as related to grain refining [4, 5]. However, the following question arises: Is the prevalence of Al-Si-Mg alloys due to a tradition established over the years rather than to a rational balance between the expected difficulties in pouring Al-Cu alloys and the far superior mechanical properties they provide? The foundry practices pertaining to these alloys have been outlined in an AFS webinar [6]; it attests to the fact that, in sand casting, exceptionally strong, sound Al-Cu castings can be routinely obtained through current “good foundry practices”, by implementing process control tools readily available. For structural castings where weight gains are important, aluminium A206 can even substitute ductile iron as is the case for the casting shown in Figure 1. In the T4 condition, important internal stresses generated in the quenching will make machining problematic as distortion is bound to occur at each machining pass. This can be alleviated by practicing a stress relief treatment (T43 per ASTM B917) consisting in heating the T4 casting for one hour at 160 °C. Caution should be exercised in not overdoing it so as to avoid making the casting vulnerable to stress corrosion [3].

Figure 1. Aluminum A206 -T4 knuckle substituting ferritic ductile iron.
(*Courtesy of Eck Industries)*

In alloy A206, the chemical requirement on Fe and Si is very stringent: 0.10 % Fe and 0.05 % Si maximum. Alloy A206 is always used in a heat treated condition, the T4 (solutionized, quenched and naturally aged) being preferred when ductility and endurance are sought, rather than strength. The T7 condition is obtained by aging the T4 casting for 5 h at 190 °C, resulting in an increased tensile strength to the detriment of elongation. Typically, aging a T4 treated A206 casting to a T7 temper increases its yield strength by 40 % while dividing its elongation by 2 to 3 [8]. This T7 treatment provides tensile properties which exceed those of grey iron, comparing to those of ferritic ductile iron.

Peak aging (T6) is not practical as it lead to a condition prone to stress corrosion cracking [3].
In the course of casting runs, as the charge contains typically 50 % of returns, the melt content in Fe and Si tends to rise and stabilize to values above the very stringent specifications of A206; The alloy can thus be downgraded to 206 and 204. The effect of these elements on tensile properties has been previously studied under laboratory conditions, first on a wedge casting with extremely long solidification time [7], and in permanent mold, on ASTM B108 tensile test bars where the solidification time is of the order of 30 s [9,10]. The present work will involve conditions much closer to foundry practices: sand casting with solidification times ranging between 0.67 to 4.8 minutes.

2. Experimental Procedure

High Si and Fe content Al-Cu aluminium 204 alloy melts (gassed and degassed) were direct-poured at 740 °C into step molds cavity via a Kalpur filter cup, as illustrated in Figure 2. A 10 p.p.i. filter at the bottom of the cup prevented the excessive turbulence which a top poured casting would entail. Figure 3 shows the casting after shake-out on the left; on the right, a section of the step casting and attached direct-pour cup is sketched with the successive plate thickness of 25mm, 13mm, 6mm and a 2mm flow-off. The composition is given in Table 1.

Table 1. Chemical composition of the Al-Cu aluminum 204 melts (gassed and degassed).

	%Si	%Fe	%Cu	%Mn	%Mg	%Zn	%Ti
Weight %	0.23	0.12	4.23	0.33	0.14	0.06	0.25

Figure 2. Step casting model with Kalpur filter cup – Mold before pouring.

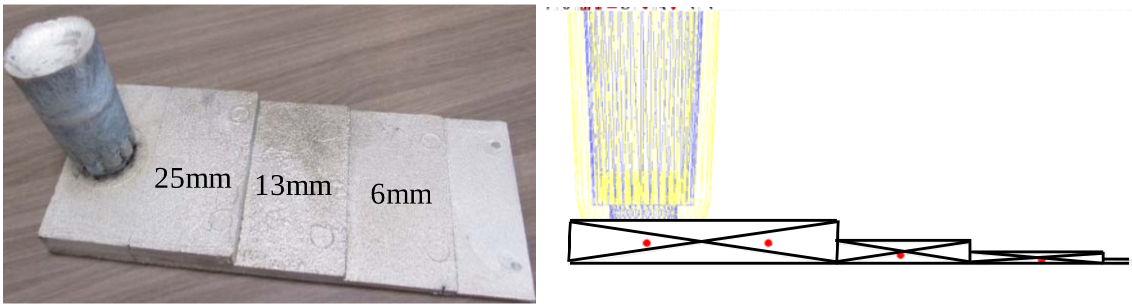

Figure 3. The step casting at shake-out (left) – Sketch of the sectioned step casting.

The recordings of three thermocouples inserted in one step casting and cup, along with filling and solidification modeling allowed to predict the solidification times at the locations indicated by the red dots in Figure 3; from left to right, the local solidification times were: 7.0, 4.8, 2.0 and 0.67 min. Four step castings of high Si and Fe Al-Cu alloy were poured after a thorough degassing to a reduced pressure test (RPT) sample density of 2.72 (Figure 4, left). The same alloy was treated with gassing tablets to a reduced pressure test sample density of 2.48 (Figure 4, right) before pouring four additional step castings. These RPT samples were obtained under a partial vacuum of 0.1 bar, corresponding to a hydrogen content of about 0.1 and 0.3 ppm, respectively.

Figure 4. Reduced pressure test of the degassed and gassed melts (d= 2.72 and 2.48).

Four step casting were also poured from a degassed premium A206 melt using a similar procedure. These samples will be used as a benchmark to assess the deleterious effects of gassing and tramp elements (Si, Fe).

3. Grain Size and Porosity in the Step Castings

The metallographic images inside the A206 casting shown in Figure 5 indicate an increase in the grain size from 137, 192 and 235 µm for the 6 mm, 13 mm and 25 mm plates, as measured according to the ASTM E112-13 standard. The etchant used was an aqueous solution of 0.5 % HF. Let us remind that the solidification times at the center of the 6 mm, 13 mm and 25 mm plates were 0.67 min, 2.0 min and 4.8 min respectively.

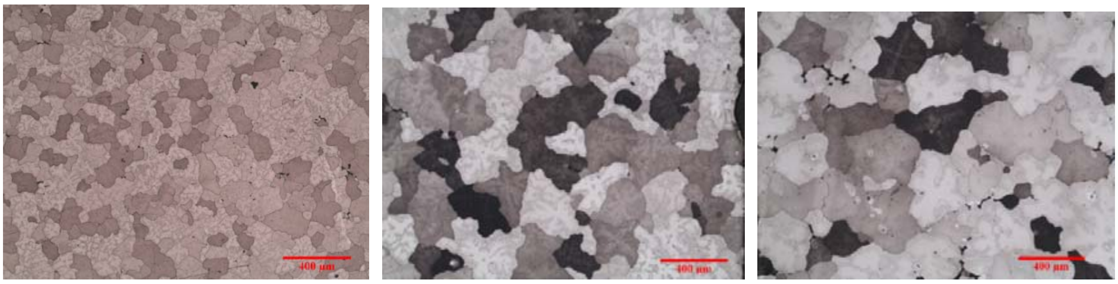

Figure 5. Metallography in the 6 mm, 13 mm and 25 mm plates of a degassed A206 step casting, from left to right.

Figure 6 shows the mosaics of the same plates unetched, with porosity level of 0.10, 0.14 and 0.43 %, as measured by image analysis; they compare to plate densities of 2.807, 2.806 and 2.785, as measured by Archimedes' method, or 0.10, 0.11 and 0.88 %. The agreement between the image analysis and Archimedes' results is not perfect because the latter measures the volume porosity over the whole plate rather than a surface porosity in a particular plane.

Figure 6. Mosaic in the 6 mm, 13 mm and 25 mm of the degassed A206 step casting.

The Archimedes' porosity levels were similar in the degassed 204 step casting: 0.43, 0.60 and 0.73 % for the 6 mm, 13 mm and 25 mm plates. Figure 7 shows the equivalent of Figure 6 in the gassed 204 step casting with surface image analysis porosity of 1.30, 1.89 and 2.36 % and volume Archimedes' porosity of 1.50, 1.70 and 2.90 % for the 6 mm, 13 mm and 25 mm plates respectively.

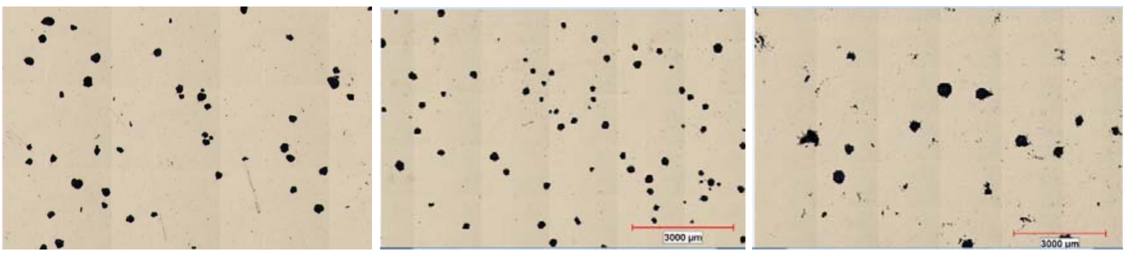

Figure 7. Mosaics in the 6mm, 13 mm and 25 mm plates of the gassed 204 step casting.

4. Tensile Properties as a Function of Thickness and Porosity

Half the plates were heat treated to a T4 temper, and the other half to a T7 heat treatment according to ASTM B917M-11. Tensile test bars were excised from the step castings according to the sketch shown in Figure 8.

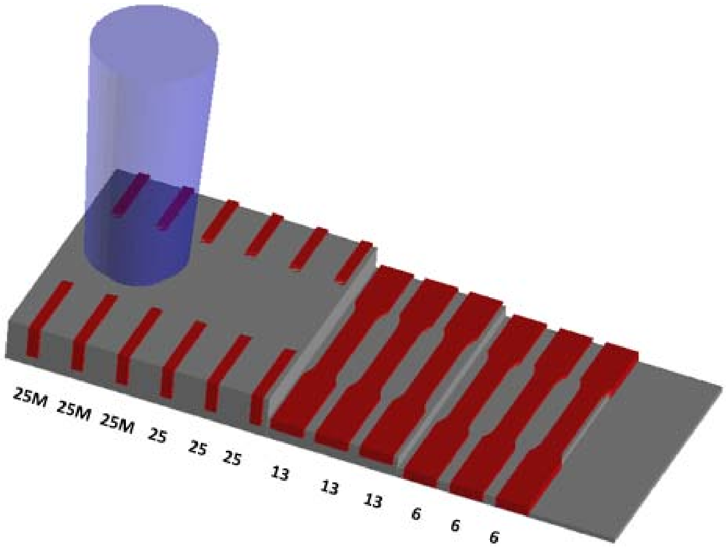

Figure 8. Tensile test bars cut from the step casting; 6 mm x 13 mm in the reduced section.

For each heat treatment condition (T4 and T7), 6 samples were available for each of the step casting plates (6mm, 13mm and 25mm) in the degassed and gassed conditions; the tensile properties (Yield strength YS, ultimate tensile strength UTS and elongation El) will thus be obtained by averaging 6 results. The tensile samples marked 25M in Figure 8 were not used in the present study. The noblest Al-Cu alloy available on the market is alloy A206, with very stringent upper limits on silicon and iron: 0.05 and 0.10 weight %, respectively. In order to assess the detrimental effect of these elements on the tensile properties, alloy A206 was used as a benchmark and step castings were poured with the alloy composition given in Table 2. Note the very low Si and Fe contents of 0.04 and 0.05 % in the A206 alloy, versus 0.23 and 0.12 % in the high Si and Fe content alloy 204 studied in the present work.

Table 2. Chemical composition of the "benchmark" aluminium A206 melt.

	%Si	%Fe	%Cu	%Mn	%Mg	%Zn	%Ti
Weight %	0.04	0.05	4.55	0.35	0.25	< 0.01	0.19

The graphs of Figure 9 and 10 plot the yield strength (YS), ultimate tensile strength (UTS) and elongation (El) for aluminium A206, degassed and gassed aluminum 204 in the T4 and T7 conditions. Each result is obtained as an average of 6 tensile tests (3 sample per thickness from 2 step castings). In the T4 temper, the average standard deviations on YS, UTS and El were 9.3 MPa, 17 MPa and 1.5 % for A206 and 11 MPa, 19 MPa and 2.3 % for alloy 204 (gassed and degassed). In the T7 temper, the averages of the standard deviations were 19 MPa, 22 MPa and 0.6 % for A206 and 23 MPa, 26 MPa and 0.9 % for the high Si and Fe content alloy 204.

The charts show the effect of the Si and Fe tramp elements (Alloy A206 vs alloy 204). They also show the detrimental effect of the gas content by comparing degassed alloy 204 to gassed alloy 204G. It can be seen that a longer solidification time (thicker plate) results in a small drop in the ultimate tensile strength and elongation while the yield strength remains virtually unchanged. On the other hand, tramp elements (Si, Fe) decrease the yield strength in the T4 conditions and increase it in the T7 temper; they reduce the elongation much more in the T7 than in the T4 temper (typically by 70 % vs 40 %). Gassing reduces the yield and ultimate strength in the T4 and T7 conditions; it also reduces the elongation in the T4 condition while having a much lesser effect on ductility in the T7 temper.

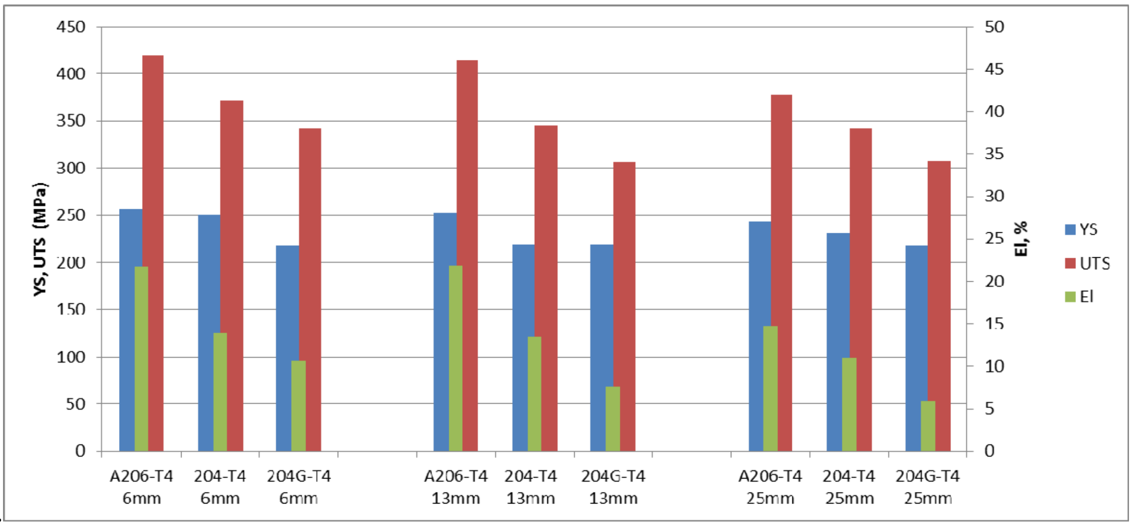

Figure 9. Tensile properties in alloys A206, degassed and gassed 204 in the T4 condition.

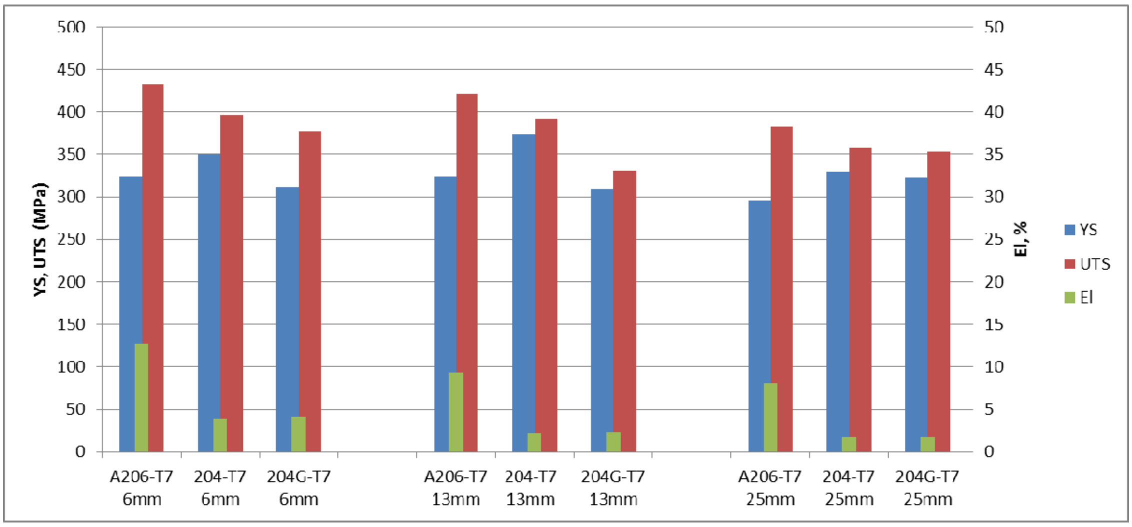

Figure 10. Tensile properties in alloys A206, degassed and gassed 204 in the T7 condition.

The concept of "Tensile Potential" TP, allows to lump strength and ductility into a unique property. It is defined as TP = YS + 260 Log El [8] and is a measure of the mechanical resistance of the alloy, taking into account both strength and elongation; its mathematical expression has been selected so that TP should be similar in the T4 or T7 temper. The graphs of

Figure 11 compares the Tensile Potential for all the conditions investigated, namely: alloy purity (A206 vs 204), solidification time (via the plate thickness) and gas content (204 vs 204G). The graph of Figure 11 confirms that the Tensile Potential values are similar in the T4 and T7 temper.

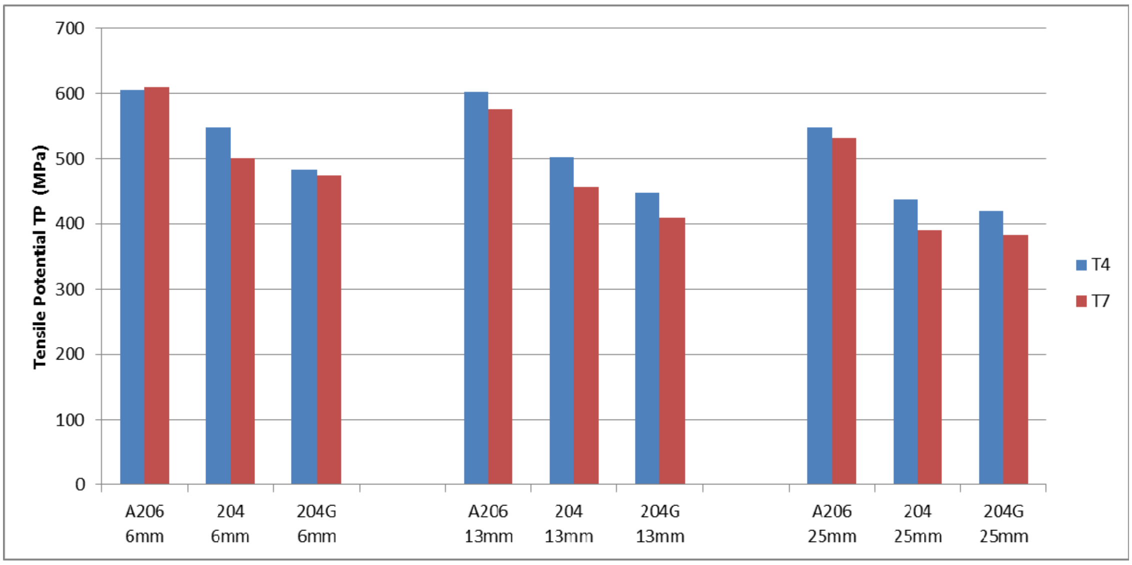

Figure 11. Effect of alloy purity, gassing and thickness on the tensile potential of Al-Cu alloys.

5. Conclusions

A thorough metallurgical study on Al-Cu alloys step castings (6 mm, 13 mm and 25 mm thick) in which the solidification time varied from 0.67 to 4.8 minutes allowed drawing the following conclusions:

1) Among the three tensile properties measured, the yield strength YS is the least dependent on the metallurgical quality of the alloy (level of tramp elements and gassing); YS lies in the range 200 - 250 MPa in the T4 temper and 300 - 350 MPa in the T7 condition.
2) Tramp elements (Si, Fe) drop the yield strength in the T4 temper with an opposite effect in the T7 condition. They reduce the ultimate tensile strength and elongation in both T4 and T7 conditions; however the effect is more marked in T7.
3) Gassing reduces the yield and ultimate strength in the T4 and T7 tempers; it also reduces the elongation in the T4 condition but not in the T7 temper.
4) In summary, the ultimate tensile strength UTS and elongation El are strongly dependent on the metallurgical quality of the alloy as defined by a low Si and Fe content and a thorough degassing. El lies in the range, 15 – 22 % for the top quality A206-T4 alloy and 8 – 12 % for A206-T7. These ranges drops to 12 – 14 % for degassed 204-T4 and 6 – 10 % when gassed. In the T7 temper, the elongation of alloy 204 lie in the range 2 – 4 % irrespective of the level of gassing.

Overall, it can be concluded that for the present casting conditions, a high level of tramp elements (0.23 Si, 0.12 Fe versus 0.04 Si, 0.05 Fe for A206) has been more detrimental to tensile properties than gassing in the 204 alloy (1.5 to 2.9 % porosity versus 0.43 to 0.73 % for the degassed alloy); this is particularly true for the elongation in the T7 condition where the effect of gassing is minimal.

6. Acknowledgments

The authors wish to acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada for funding the Chair on the Transformation of Aluminum at Centre de Métallurgie du Québec. They wish to recognize the contribution of Justin Plante, an intern student from Laval University. Part of this work has been supported by the REGAL Aluminium Research Centre in which CMQ partners with 7 Quebec universities.

7. References

1. S. Li, D. Apelian, Hot tearing of aluminum alloys, a critical review, *International Journal of Metal casting*, Vol. 5, No 1, 2011, 23-40.
2. J. Cho, X. Yan, C.R. Loper Jr, Microsegregation of copper in cast aluminum alloys, Transactions of the American Foundry Society, Vol. 111, 2003, 315-331.
3. D. Jean et al., Heat treatment and corrosion resistance of B206 aluminum alloy, *Transactions of the American Foundry Society*, Vol. 117, 2009, 113-129.
4. G.K. Sigworth, F. DeHart, Recent developments in the high strength aluminum-copper casting alloy A206, *Transactions of the American Foundry Society*, Vol. 111, 2003, 113-129.
5. D. Jean, J.F. Major, Chemistry / property relationships in AA206 alloys: Fatigue behavior, *Transactions of the American Foundry Society*, Vol. 117, 2009, 103-112.
6. D. Weiss, Enhancing Aluminum Castings for Structural Applications, AFS Webinar, http://www.afsinc.org/multimedia/MCTVDetail.cfm?ItemNumber=16259, 52 min, 2014.
7. A. Rodriguez et al., The effect of solidification conditions and alloy composition on the castability and mechanical properties of B206 alloy, *Transactions of the American Foundry Society*, Vol. 117, 2009, 79-91.
8. F. Chiesa et al., Metallurgical properties inside a sand molded aluminum 206 casting, *Transactions of the American Foundry Society*, Vol. 124, Paper 16-002, 2016, 12 p.
9. K. Liu et al., Effects of iron-rich intermetallics on tensile deformation of Al-Cu 206 cast alloys", *Metallurgical and Materials Transactions B*, Vol. 46b, 2015, 1566-1575.
10. H.K. Kamga, Mechanical properties of aluminium–copper B206 alloys with iron and silicon additions, *International Journal of Cast Metal Research*, Vol. 15, 2012, 15-25.