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Evaluation of the mechanical properties of AA 5052 and AA 5050C aluminum alloy rolled sheets

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Abstract: *This study was conducted on AA 5052 sheets produced by direct casting and AA 5050C produced by twin roll casting, to microstructurally and mechanically characterize these alloys and evaluate dynamic aging occurrence as a function of the strain rate applied in uniaxial tensile tests. In general, AA 5052 alloy showed higher strength values and lower ductility. Analysis of the aspect of tensile curves showed serrations in both alloys, indicating rapid and successive stresses variations in the plastic deformation region for both alloys, suggesting dynamic aging occurrence and how this effect is more pronounced at lower displacement speed. The frequency and magnitude of the decrease stress can be associated with the distinct Mg content of the alloys, being smaller in the AA 5050C.*

KEYWORDS: *5xxx aluminum alloys, Direct chill process, Twin roll caster process, mechanical properties, aging dynamic.*

Resumo: *Este estudo foi conduzido em chapas das ligas AA 5052, produzida por processo de fundição direta (DC), e AA 5050C, produzida por processo de fundição contínua de chapas (TRC), com o intuito de caracterizar microestrutural e mecanicamente as referidas ligas, assim como avaliar a ocorrência de envelhecimento dinâmico em função da taxa de deformação aplicada em ensaios de tração uniaxial. De maneira geral, observou-se valores superiores de resistência e menor ductilidade para a liga AA 5052, e ao analisar o aspecto das curvas de tração, pôde-se verificar a presença de serrilhados em ambas as ligas, indicativos de variações rápidas e sucessivas de tensões, na região de deformação plástica, sugerindo a ocorrência do envelhecimento dinâmico, e como, em menor velocidade de deformação, esse efeito é mais pronunciado. A frequência e magnitude de quedas de tensão verificadas podem ser associadas principalmente aos diferentes teores de Mg das ligas, sendo menor para a liga AA 5050C que possuí menor teor de Mg.*

PALAVRAS-CHAVE: *Ligas de alumínio 5xxx, processo de fundição contínua, processo de fundição direta, propriedades mecânicas, envelhecimento dinâmico.*

1. Introduction

Aluminum alloys, due to their interesting combination between strength and weight, good conformability, and high corrosion resistance, among other characteristics, have stood out as a viable alternative for applications in the automotive industry in the production of components or structural parts, and have gained prominence mainly for applications in bus bodies due to the possibility of reducing the weight of automobiles, resulting in reduced fuel costs and gas emissions [1].

However, such applications are still restricted due to the complex technology and high cost of aluminum production when compared to steel. The most used method for the manufacture of aluminum alloys in the form of plates is based on the direct casting process (*Direct Chill – DC*).

The direct chill (DC) process consists of the casting of plates, followed by a machining and hot rolling process, in order to significantly reduce the thickness of the plate in a hot plastic forming process. Subsequently, the sheet goes to cold rolling, which increases its mechanical properties in terms of strength, combined with the decrease in ductility, and in some cases, subsequently goes to annealing heat treatment for stress relief/stabilization or partial/total recrystallization, according to the final application [2,3].

Another way of obtaining aluminum laminates and their alloys is through the Twin roll caster (TRC) process, in which the manufacture of hot rolled and coiled sheets occurs directly from the liquid metal.

The process consists in a combination of the material solidification and hot rolling steps, which allows the sheet, in the form of a coil, to proceed directly to the cold rolling process [4,5].

Aluminum sheets processing through twin roll casting (TRC) reduces not only the costs in the manufacturing process, but also processing time. Such characteristics, combined with the ease of changing the thickness and width of the casting without the need to change the dimensions of the mold, make production more agile and advantageous [5].

Aluminum alloys of different series are usually produced from the DC process and are later laminated (by hot and cold processes) and annealed, but the production of some of them on a laboratory and industrial scale by the TRC process is also observed, with some reservations. The literature highlights that alloys with a narrow solidification interval are largely produced in several dimensions by the TRC process. However, for alloys with a wide solidification range, the process is still limited, not allowing one to obtain a final product with the appropriate mechanical properties [6]. Another limiting factor is the chemical composition of the alloys, some of which can present major problems related to the formation of segregation centerlines and of an excessive oxide layer, such as the alloys of the 5xxx series. This factor was present in the Companhia Brasileira de Alumínio (CBA), in Alumínio/São Paulo (SP), when trying to produce the AA 5052 alloy in its original composition by TRC, being possible to circumvent the problem only with the compositional adjustment that resulted in the AA 5050C alloy [7], being both objects of this study.

Another aspect of the laminated products of the 5xxx series alloys is that they are likely to present dynamic aging as a function of the strain rate to which they are subjected, even at room temperature, which is revealed by serrations in the stress-strain curve [8,9]. The justification for this behavior – the serrated pattern – is attributed to the abrupt movement of dislocations, which results in the dynamic interaction of dislocations with substitutional solute atoms present in the solid solution [9]. In this perception, one assumes the movement of dislocations is prevented by solute atoms that isolate them; consequently, an increased tension is necessary for the dislocations to be unlocked, resulting in a negative tension/deformation, leading to flow instability, i.e., the Portevin-Le Chatelier (PLC) effect.

Therefore, this study aimed to perform a microstructural and mechanical characterization of laminated and annealed AA 5052 and AA 5050C aluminum alloy sheets, produced by CBA from DC and TRC processes, respectively, as well as to evaluate the occurrence of aging in the alloys when mechanically requested via uniaxial tensile test at two different speeds and at room temperature.

2. Material and Methods

The materials under study, provided by the company Companhia Brasileira de Alumínio (CBA) – located in Alumínio - SP, consist of two aluminum alloys of the 5xxx series, AA 5052 and AA 5050C – according to the chemical composition presented in Table 1 – which were produced by different processes, the first via direct chill (DC) and the second by twin roll casting (TRC). These alloys were subsequently subjected to the same processing route and parameters until obtaining thin sheets with approximately 1.20 mm thickness in the final cold rolled and annealed/stabilized condition, as shown in Figure 1, which will only be distinguished by the value of the total reduction in the first cold rolling step (68.3% for alloy 5052 and 72.8% for alloy 5050C) and soaking temperature in the intermediate annealing (360°C for alloy 5052 and 380°C for alloy 5050C).

Table 1 - Chemical composition of the alloys under study, with emphasis on the elements of alloys and residuals, % in weight.

Si	Fe	Cu	Mn	Mg	Ti	Cr
AA 5052						
0.06	0.26	0.06	0.06	2.41	0.20	0.01
AA 5050C						
0.07	0.47	0.36	0.10	1.39	0.00	0.04

Source: CBA.

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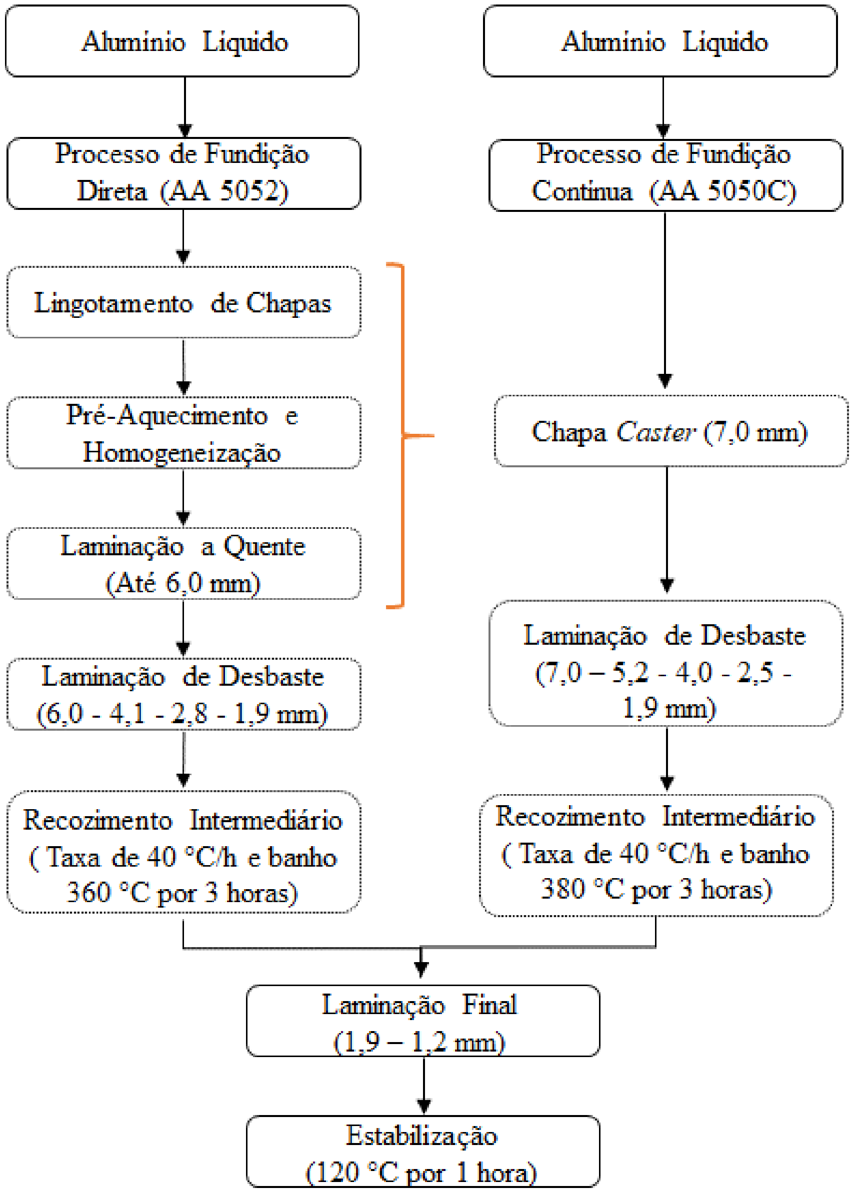
Figure 1 - Processing steps in the CBA of the 5xxx series alloys under study.



Source: CBA.

Microstructural characterization was conducted with the aid of a scanning electron microscope with a field emission cannon, FEI Quanta FEG, observing the samples in the thickness of the plate, in the plane containing the lamination direction (DL), after metallographic preparation: sanding from 220 to 4000 mesh, polishing in 3 and 1 μm diamond paste, and a final electrolytic polishing with perchloric acid solution (20% $HClO_4$ + 80% C_2H_5OH) for 5 seconds at 10 Volts, at room temperature.

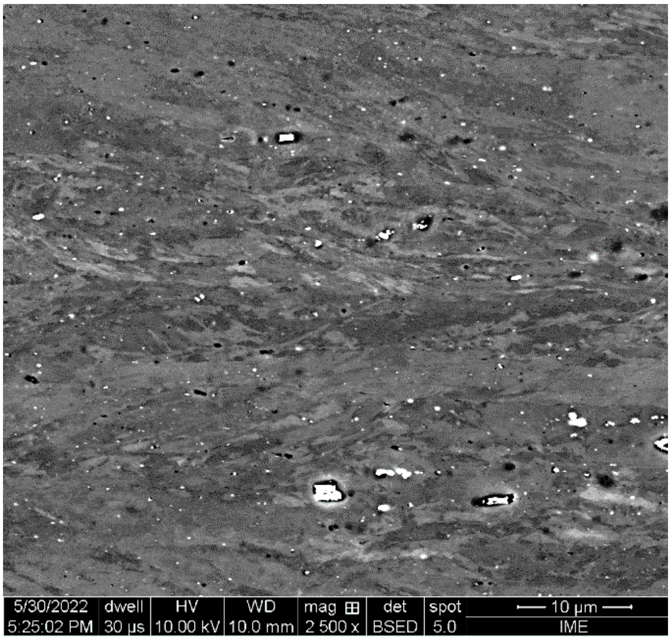
For mechanical characterization, Vickers hardness and uniaxial tensile tests were performed. The hardness test was conducted with 10 measurements for each sample along the plate plane, with a load of 10 kgf. Whereas the uniaxial tensile test was conducted on specimens made according to ASTM E8/E8M

[10] under two conditions of crossbar displacement speed (2 and 7 mm/min), using different strain gauge technologies (contact for speed of 2 mm/min and optical for speed of 7 mm/min), in order to ascertain the occurrence of dynamic aging as a function of the deformation speed.

3. Results and Discussion

Figures 2 and 3 show results from the microstructural analysis via Scanning Electron Microscopy (SEM) using the backscattered electron detector (BSE) of AA 5052 and AA 5050C alloys, respectively.

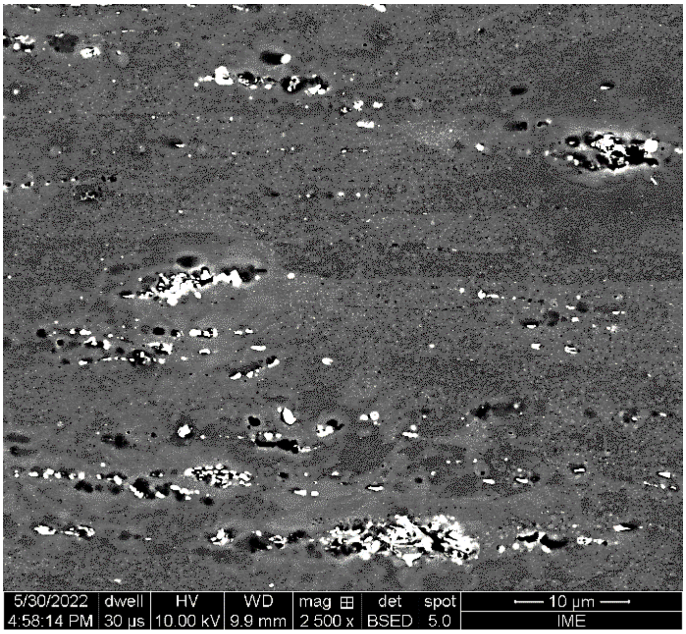
Figure 2 - Micrograph of AA 5052 alloy (DL, with arrows indicating cavities (in black) that contained parts of the possible inclusion particles/precipitates still present (in white).



Source: Prepared by the authors.

One can see homogeneous and similar distribution of inclusions and/or precipitates along the samples aligned in the DL, and that the alloy produced by the twin roll casting process (AA 5050C) apparently presents inclusions/second phase particles in greater amount distributed along the matrix in relation to the alloy produced by the direct chill process (AA 5052). This can be explained in two possible ways. The first possibility may be associated with the higher solidification rates obtained in the twin roll casting process, which favors the formation of a greater number of sites for second phase nucleation [11]. The second possibility, if most of these particles are associated with inclusions, refers to the fact that the ingot produced by direct chill – DC, the AA 5052 alloy, is subjected to a surface scarfing process before being hot rolled, which guarantees the removal of much of the alumina (Al_2O_3) layer formed on the surface of the ingot, while the product of twin roll casting – TRC, the AA 5050C alloy, keeps in its volume all the alumina formed during the casting process combined with hot rolling. One also observed that electrolytic polishing promoted the removal of part of the inclusions and/or precipitates due to the anodic behavior in the formed electrolytic cell, giving rise to the cavities presented together with the metal matrix in these microstructures, as highlighted in Figures 2 and 3.

Figure 3 - Micrograph of AA 5050C alloy (DL→), with arrows indicating cavities (in black) that contained parts of the possible inclusion particles/precipitates still present (in white).



Source: Prepared by the authors.

Table 2 shows the results of the Vickers hardness test performed. The average hardness values presented in the alloys showed a significant difference, and it was possible to observe a reduction of 21.78% in the hardness value for alloy AA 5050C compared to AA 5052. Considering the variance calculated and reliability of the results obtained in the test, one should emphasize there was no significant dispersion between the values obtained for each alloy under study.

Table 2 - Results of the Vickers hardness test.

	AA 5052	AA 5050C
Mean	87.38	68.35
Standard Deviation	2.42	1.38
Variance	5.86	1.91
Minimum	83.59	65.64
Maximum	91.17	69.92
Number of measurements	10	10
Reliability index (95%)	1.50	1.18

Source: Prepared by the authors.

The AA 5050C alloy, due to its greater number of inclusions and/or second phase particles dispersed in the matrix by its production via twin roll casting process, was expected to be harder than AA 5052. This fact is not observed and can be explained by the compositional difference of the alloys (Table 1). The AA 5050C alloy is a compositional adaptation of AA 5052 alloy, aimed at reducing the oxide layer formed during TRC processing. Magnesium was one of the altered elements, having its amount reduced, and because it is an element that is preferably found in solid solution, this reduction in content directly affects the hardness and mechanical strength of the alloy. These indications highlight that these particles observed in SEM analyses are probably largely associated with alumina (Al_2O_3) inclusions, which have no role in alloy hardening, as it occurs with the second intermetallic phase particles formed in this type of alloys. Another point that supports the lower hardness behavior for the 5050C alloy are the conditions under which it was subjected to thermomechanical processing, i.e., the highest total reduction applied in the first cold rolling step and the highest soaking temperature to which it was exposed in the intermediate annealing (Figure 1). These factors may have provided reduced recrystallization temperature (by the reduction imposed on the thinning lamination) plus the possibility of grain growth (by the soaking temperature imposed on the annealing for recrystallization) in the condition that was subsequently subjected to final cold rolling and annealing for stabilization, thus also contributing to the decrease in hardness.

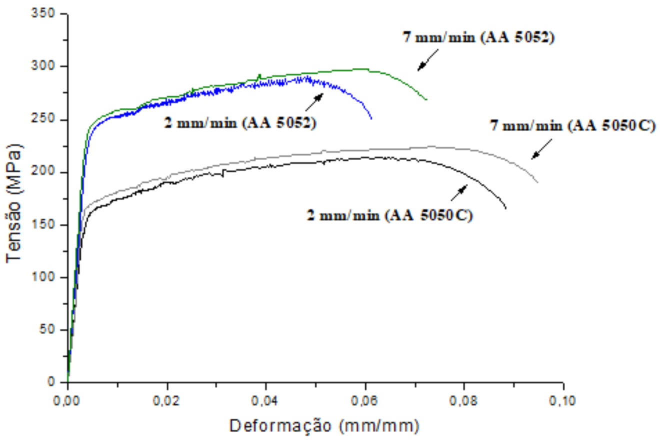
Figure 4 shows the engineering stress-strain curves of alloys AA 5052 and AA 5050C, with strain speeds in the uniaxial tensile test of 2 mm/min and 7 mm/min.

Regarding the aspect of the curve, serrations caused by the Portevin-Le Chatelier effect, or dynamic aging behavior, are observed in the plastic deformation region of both alloys tested at a speed of 2 mm/min. The AA 5052 alloy exhibits not only a higher magnitude of voltage dips (difference between peak and valley voltage in each dentition), but also a higher frequency (number of voltage dips) when compared to AA 5050C.

According to the dynamic stress aging model, when the movement of dislocations is temporarily interrupted in obstacles, such as forests of dislocations, the solute atoms that are already isolated in these obstacles migrate toward these fixed dislocations. They then form atmospheres around the dislocations and cause them to be blocked. When the applied force is high enough, the movable dislocations detach from the atmospheres and advance freely toward other obstacles. The repetition of this process constitutes the serrated production observed in the stress-strain curve [12].

Thus, one can infer that, as the AA 5052 alloy has a higher concentration of magnesium (Table 1), most of the Mg solute atoms move in the direction of the dislocations and, therefore, unlocking such dislocations is more difficult. Therefore, a greater force is required to move the dislocation, resulting in a greater stress drop in the stress-strain curve. On the other hand, when the magnesium concentration is high, the interaction of magnesium solute atoms with the dislocations is more frequent and, consequently, the process of voltage drops becomes more frequent. One can see that serration occurs at a higher frequency for AA 5052 than for the AA 5050C alloy.

Figure 4 - Engineering stress-strain curves of alloys AA 5052 and AA 5050C, with strain speeds in the uniaxial tensile test of 2 mm/min and 7 mm/min.



Source: Prepared by the authors.

For the curves tested with a deformation speed of 7 mm/min, there is, as expected, a decrease in the amount and intensity of serration. This fact occurs due to the increase in deformation rate, since there is no time for the movement of the solute atmosphere, which is responsible for dynamic aging. Thus, this test speed is not sufficient to eliminate serrations, however, the voltage drops become less frequent.

Table 2 shows the mechanical properties of alloys AA 5052 and AA 5050C obtained through uniaxial tensile tests performed with a deformation rate of 2 mm/min and 7 mm/min.

Table 2 - Mechanical properties of AA 5052 and AA 5050C alloys extracted from tensile tests.

Properties	Strain Speed (mm/min)			
	AA 5052		AA 5050C	
	(2)	(7)	(2)	(7)
Yield strength (σe) (MPa)	240.74 ± 8.06	254.26 ± 6.13	156.61 ± 6.96	169.88 ± 0.41
Elasticity Modulus (E) (GPa)	66.78 ± 5.83	71.84 ± 6.36	68.58 ± 11.68	73.52 ± 13.38
Tensile Strength Limit (LRT) (MPa)	286.76 ± 9.39	298.91 ± 20.47	211.13 ± 2.39	209.46 ± 0.48
Uniform Elongation (%)	4.24*	5.44*	5.91*	5.69*
Elongation at break (%)	4.82*	6.05*	6.60*	6.32*

***Data extracted from the stress-strain curves in Figure 4.**
Source: Prepared by the authors.

As for the mechanical properties observed in the tensile test, it is possible to verify that the AA 5052 alloy presented higher values of tensile and yield strength and lower values of elongation when compared to the AA 5050C alloy, as also observed in the hardness test. According to the literature, materials processed by twin roll casting (TRC) have superior mechanical properties in terms of strength when compared to those produced by direct chill casting (DC). This fact stems from the presence of a greater number of second phase precipitates during TRC, where the precipitates are possibly anchored, preferably, in the grain contours, acting as grain refiners [13]. Analyzing the Hall-Petch equation, it is observed that the relationship between grain size and stress are inversely proportional, i.e., the smaller the grain size, the greater the tensile strength of the material. It is inferred, through the mechanical properties obtained, that the alloys under study presented behavior contrary to that presented in the literature.

This behavior can be explained by the difference in composition between the alloys, since the AA 5050C alloy has a lower magnesium and chromium content and a higher copper content, added to the fact that it was subjected to a greater reduction in thickness and higher soaking temperature in the processes subsequent to hot rolling, that is, from cold rolling to roughing and intermediate annealing for recrystallization, which were adopted for the AA 5052 alloy, before being subjected to conditions similar to the alloy 5052 in the final lamination and annealing for stabilization (Figure 1). This compositional variation was necessary to reduce surface oxidation during solidification in TRC processing. Thus, despite having the propensity to present more refined grains by the TRC process, in relation to the AA 5052 alloy, the AA 5050C alloy has lower limits of tensile and yield strength, and higher ductility, probably justified by the lower hardening by solid solution and/or precipitation, due to the composition, added to the larger grain size due to the intermediate processing (as shown in Figure 1).

Regarding the use of different test speeds in uniaxial traction, comparing the results obtained, one observed that these presented differences for the values of yield strength, elasticity modulus, strength limit, and elongation. This effect in relation to the values of yield, strength, and elongation limits can be explained due to the increased number of stacked dislocations due to the increased deformation rate, which causes greater resistance in the beginning of deformation, greater hardening and extension in the plastic deformation capacity, in the uniform deformation regime, and located in the stricture [14]. However, in relation to the modulus of elasticity, the difference can be attributed to the fact that the test was conducted with different strain gauge technologies (contact for a speed of 2 mm/min and optical for a speed of 7 mm/min).

4. Final considerations

Mechanical strengths presented by the properties of the AA 5052 alloy, such as yield and tensile strength, were higher than those presented by the AA 5050C alloy, both in uniaxial traction and Vickers hardness testing, unlike the lower ductility. This result can be explained by variations in the chemical compositions of each alloy and in the production processes. It is possible that small decreases in temperatures and/or soaking time in the intermediate annealing and stabilization treatments provide adjustments that would result in close values of properties of both alloys subjected to distinct reductions in thinning cold rolling and the like in the final cold rolling, without further adjustments in the chemical composition of the alloy 5050C.

Thus, the AA 5050C alloy can be considered as a viable option to replace the AA 5052 alloy for applications that do not require high mechanical strength and exhibit greater ductility under the processing conditions adopted for this study.

As for the occurrence of dynamic aging, the presence of serrations in the region of plastic deformation in both alloys indicates the existence of the phenomenon. The frequency and magnitude of voltage drops verified can be associated with the different Mg contents of the alloys, depending on their presence in solid solution. It is also observed that the increase in the deformation speed from 2 mm/min to 7 mm/min during the tensile test promotes a decrease in the amount and intensity of serrations, as well as a greater extension in the uniform and total elongation, probably due to the reduction of the time for the movement of the solute atmosphere during the sliding of dislocations. That is, the forming processing of these alloys to obtain parts can be easily performed without the occurrence of dynamic aging when performed under higher strain rates.

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Bibliographic References

[1] ABAL – ASSOCIAÇÃO BRASILEIRA DO ALUMÍNIO. Vantagens e desvantagens do alumínio. *Abal*, São Paulo, [20--?]. Disponível em: https://abal.org.br/aluminio/vantagens-do-aluminio/. Acesso em: 27, jul. 2018.

[2] OTOMAR, H. P.; PLAUT, R. L. Comparision of the microstructure and texture evolution in AA 1050 aluminum alloy sheets produced by the DC and CC methods. *In*: SUAREZ, C. E. *et al*. (org.). *Light Metals 2012*. New York: Springer, 2012. p. 223-238.

[3] DU, Q.; ESKIN, D. G.; KATGERMAN, L.; NADELLA, R. Macrosegregation in direct-chill casting of aluminium alloys. **Progress in Materials Science**, [*s. l.*], v. 53, n. 3, p. 421-480, 2008.

[4] BAREKAR, N. S.; BHAGURKAR, A. G.; DAS, S.; FAN, Z. FAKIR O. E.; HUANG, Y.; YANG, X.; ZHOU, L.; The impact of melt conditioning on microstructure, texture and ductility of twin roll cast aluminium alloy strips. **Materials Science & Engineering A**, [*s. l.*], v. 650, p. 365-373, 2016.

[5] KARLÍK, M.; ROUBAUT, F.; SLÁMA, P.; SLÁMOVÁ, M.; VÉRONA, M. Differences in microstructure and texture of Al–Mg sheets produced by twin-roll continuous casting and by direct-chill casting. **Materials Characterization**, [*s. l.*], v. 49, n. 3, p. 231-240, 2003.

[6] OGATA, C. T. **Correlações entre microestrutura, parâmetros térmicos e propriedades mecânicas de ligas de alumínio da série 5xxx solidificadas unidirecionalmente**. 2017. 106 p. Dissertação (Mestrado em Ciência e Engenharia dos Materiais) – Universidade Federal de São Carlos, São Carlos, 2017.

[7] BARONY, N. B. **Avaliação estrutural e mecânica de chapas das ligas de alumínio AA 5052 E AA 5050C**. 2019, 126 p. Dissertação (Mestrado em Ciência dos Materiais), Instituto Militar de Engenharia, 2019.

[8] CHEN, X.; FANG, Y.; MAO, J.; PAN, F.; WANG, B. Effects of cold rolling and heat treatment on microstructure and mechanical properties of AA 5052 aluminum alloy. **Transactions of Nonferrous Metals Society of China**, [*s. l.*], v. 25, n. 8, p. 2481-2489, 2015.

[9] ABOULFADL, H.; CHOI, P.; DEGES, J.; RAABE, D. Dynamic strain aging studied at the atomic scale. **Acta Materialia**, [*s. l.*], v. 86, p. 34-42, 2015.

[10] ASTM – AMERICAN SOCIETY FOR TESTING AND MATERIALS. **ASTM E8/E8M – 13a**: Standard Test Method for Tension Testing of Metallic Materials. West Conshohocken: ASTM, 2013. 28 p.

[11] HOSEINIFAR, A.; SALARI, S.; SOLTAN, M. A. N. Effect of twin-roll casting parameters on microstructure and mechanical properties of AA5083-H321 sheet. **Transactions of Nonferrous Metals Society of China**, [*s. l.*], v. 26, n. 10, p. 2552-2560, 2016.

[12] MORRIS, J. G.; WEN, W.; ZHAO, Y. The effect of Mg precipitation on the mechanical properties of 5xxx aluminum alloys. **Materials Science and Engineering A**, [*s. l.*], v. 392, n. 1-2, p.136-144, 2005.

[13] MARTINS, J. P.; PADILHA, A. F. Caracterização da liga comercial de alumínio 3003 produzida por fundição contínua de chapas (twin roll caster) – microestrutura. **Revista Escola de Minas**, Ouro Preto, v. 59, n. 4, p. 427-431, 2006.

[14] DONIČ, T.;.; KOČIŠKO, R.; KOVÁČOVÁ, A.; KVAČKAJ, M.; KVAČKAJ, T.; POKORNÝ, I. Influence of strain rate on ultimate tensile stress of coarse-grained and ultrafine-grained copper. **Materials Letters**, [*s. l.*], v. 64, n. 21, p. 2344-2346, 2010.