



RHEOLOGICAL BEHAVIOR OF SEMI-SOLID Al-Si-Cu-Mg ALLOYS

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Abstract. The goal of this work is evaluate the thixoformability of new Al-Si-Cu-Mg alloys, including the thixocasting of all alloys and their complete characterization in terms of rheological behavior. Al-1.0wt%Si-2.5wt%Cu-0.5wt%Mg, Al-2.0wt%Si-2.5wt%Cu-0.5wt%Mg, Al-4.0wt%Si-2.5wt%Cu-0.5wt%Mg and Al-7.0wt%Si-2.5wt%Cu-0.5wt%Mg alloys were produced by ultra-refining by addiction of Al-5.0wt%Ti-1.0wt%B master alloy. Materials were submitted to heating treatment for 0, 30, 90 and 210s of holding time in two conditions, 45 and 60% of solid fraction. Semi-solid behavior was evaluated by characterization of apparent viscosity. Heating treatments promoted the solid phase particles globularization. Alloys treated during 210s achieved better results and alloys containing lower solid fraction also showed better performance. 1wt% Si, 2wt%Si and 4wt%Si alloys showed very similar results in terms of apparent viscosity presenting great thixoformability potential. Better ranges for working with these new Al-Si-Cu-Mg alloys were determined reaching apparent viscosity in order to 10^5 Pa.s.

Keywords: semi-solid materials, Al-Si-Cu-Mg alloys, rheological behavior, thixoforming

1. INTRODUCTION

When thixotropic materials are sheared they flow, when allowed to stand they thicken up again; their viscosity is shear rate and time dependent. Spencer *et al.* (1972) first discovered that semi-solid alloys, which microstructure in the semi-solid state consists of spheroids of solid surrounded by liquid, present behavior similar like thixotropic materials. This particular microstructure is a requirement for thixotropic behavior and for semi-solid processing. When such material is allowed to stand, the spheroids agglomerate and the viscosity increases with time. If the material is sheared, the agglomerates are broken up and the viscosity falls. In the semi-solid state, if the alloy is allowed to stand it will support its own weight and can be handled like a solid. As soon as it is sheared, it flows with a viscosity similar to that of heavy machine oil – this is the behavior which is exploited in semi-solid processing (Kirkwood, 1994; Atkinson, 2005).

Aluminum A356 and A357 are the most common alloys used to obtain near net shape products (Chiarmetta, 2000; Kirkwood, 2001; Rosso, 2012). However, both these alloys are casting alloys, fitted to the thixoforming purpose. Thus, there is a lack of specific alloys for semi-solid processing that present good fluidity, low viscosity and small grain size – vital metallurgical characteristics that lead to the best semi-solid behavior (Flemings *et al.*, 1976). This work obtains and evaluates new Al-Si-Cu-Mg alloys with the purpose of supplying some of these gaps.

The methodology to evaluate the thixoformability of Al-Si-Cu-Mg alloys is based on the rheological behavior characterization of semi-solid materials (SSM), characterized in terms of apparent viscosity by compression tests performed at high temperatures – two conditions was chosen, 45 and 60% of solid fraction, and the alloys were submitted to heating treatment at this temperatures for 0, 30, 90 and 210s holding times and then compressed. The main goal of this work was evaluate the thixoformability of Al-Si-Cu-Mg alloys through this methodology, developing new semi-solid materials aluminum alloys and contributing to grow up of thixoforming processes.

2. EXPERIMENTAL PROCEDURE

Aluminum alloys employed in this work were produced by conventional casting from a mix of raw materials A356 alloy, commercial pure Al alloy, Mg-10.0wt%Al alloy and commercial pure Cu alloy. The method adopted to obtain a non-dendritic structure was ultra-refining through addiction of Al-Ti-B master alloy (Al-5.0wt%Ti-1.0wt%B) in approximately 0.2wt%Ti.

For rheological behavior analyses samples were heated to the semi-solid state for 0, 30, 90 and 210s holding times at 45 and 60% of solid fraction and then compressed with a compression rate of 10mm/s. Compression tests performed at high temperatures intent to determine the apparent viscosity based on Laxmanan and Flemings (1980) paper – the

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choice of this method is supported by its large operability. They were performed employing a universal testing machine model MTS-810 with 10000kgf of capacity and two Inconel 718 compression parallel plates inside a small furnace adapted to the axis of MTS system. Test output is plotted as viscosity (in Pa.s) *versus* shear rate (in s^{-1}).

Heat treatments aim to promote partial or total globularization of the alloys; by this way it is possible evaluate the rheological behavior evolution of the materials. Working temperatures, i.e., temperatures which the alloys reaches 45 and 60% solid fraction, were determined by simulation by means of software Thermo-Calc employing real composition of each alloy but without considering any residual element or possible contamination during foundry process. Routines based on non-equilibrium solidification were employed using Scheil model for this.

3. RESULTS AND DISCUSSION

All aluminum alloys were produced within the acceptable deviation range of $\pm 0.3\text{wt}\% \text{Si}$, $\pm 0.3\text{wt}\% \text{Cu}$ and $\pm 0.15\text{wt}\% \text{Mg}$ adopted. The intention was to produce semi-solid raw material via the lower cost method possible, i.e., ultra-refining. Tab. 1 shows all composition obtained.

Table 1. Chemical composition for new Al–Si–Cu–Mg alloys for thixoforming (in wt%)⁽¹⁾.

Alloy	Si	Cu	Mg	Fe	Res ⁽²⁾	Ti
Al–1.0wt%Si–2.5wt%Cu–0.5wt%Mg	1.02	2.39	0.49	0.07	0.16	0.15
Al–2.0wt%Si–2.5wt%Cu–0.5wt%Mg	2.20	2.62	0.49	0.12	0.14	0.15
Al–4.0wt%Si–2.5wt%Cu–0.5wt%Mg	4.21	2.69	0.45	0.21	0.18	0.14
Al–7.0wt%Si–2.5wt%Cu–0.5wt%Mg	6.88	2.66	0.39	0.35	0.21	0.13

⁽¹⁾ Aluminum in balance; ⁽²⁾ Sum of residual elements such Mn, Cr and Ni

Using Thermo-Calc software it was possible to determine the working temperatures, as can be seen in Tab. 2. Heat treatments were conducted based on these temperatures for each alloy.

Table 2. Working temperatures for solid fractions of 45% and 60%.

Alloy	Temperature (°C)	
	45% solid fraction	60% solid fraction
Al–1.0wt%Si–2.5wt%Cu–0.5wt%Mg	634	627
Al–2.0wt%Si–2.5wt%Cu–0.5wt%Mg	619	612
Al–4.0wt%Si–2.5wt%Cu–0.5wt%Mg	586	580
Al–7.0wt%Si–2.5wt%Cu–0.5wt%Mg	580	575

Rheological behavior according to described at experimental procedures is presented by means of Fig.1 to 4 that show viscosity *versus* shear rate for alloys at 45% and 60% of solid fraction for 1 to 7wt%Si respectively.

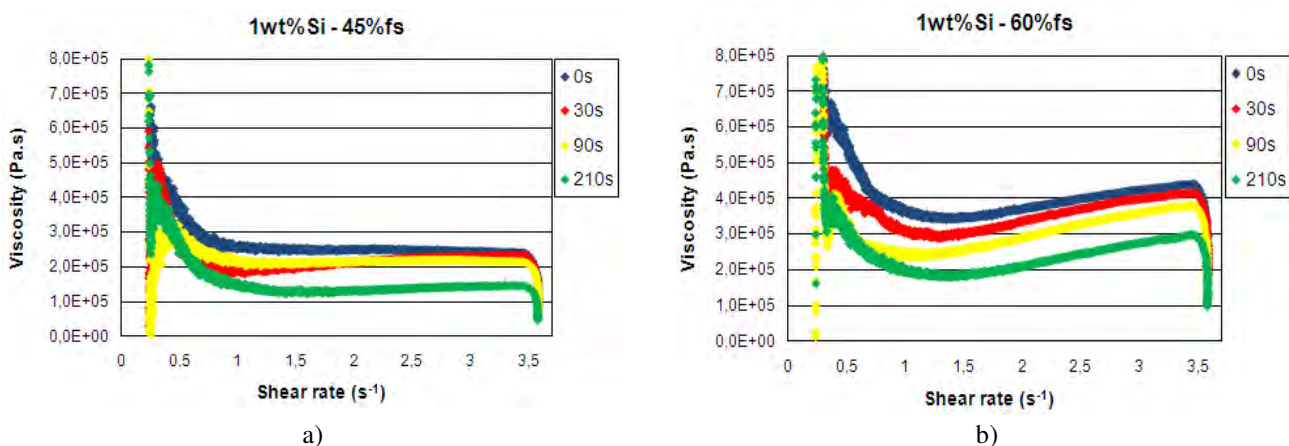


Figure 1. Viscosity *versus* shear rate curves for Al–1.0wt%Si–2.5wt%Cu–0.5wt%Mg alloys heat treated during 0, 30, 90 and 210s holding times at: a) 45% and b) 60% of solid fraction.

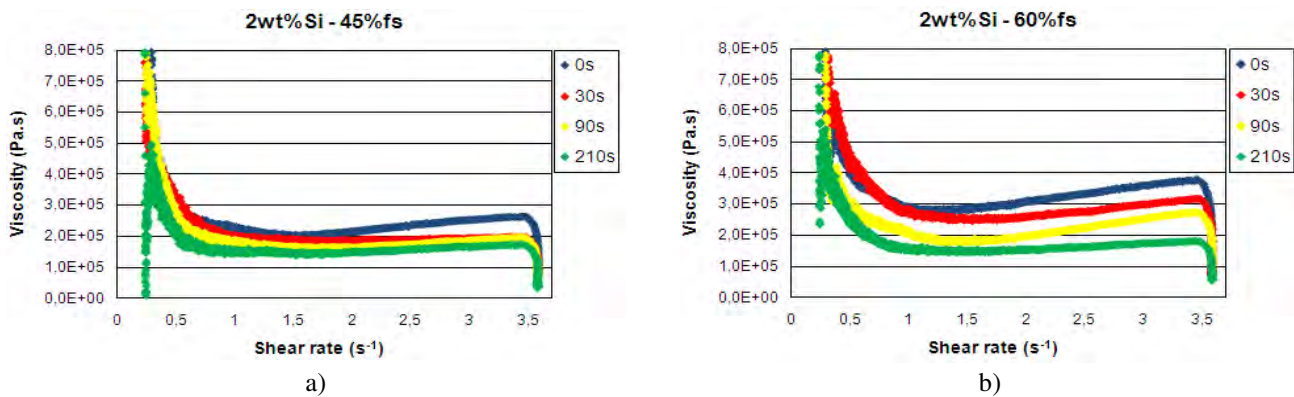


Figure 2. Viscosity *versus* shear rate curves for Al-2.0wt%Si-2.5wt%Cu-0.5wt%Mg alloys heat treated during 0, 30, 90 and 210s holding times at: a) 45% and b) 60% of solid fraction.

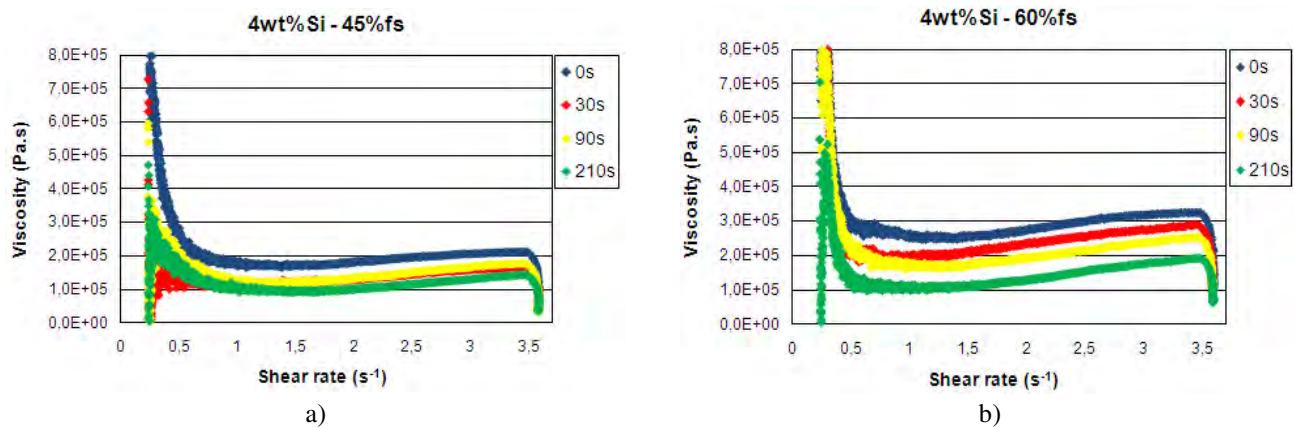


Figure 3. Viscosity *versus* shear rate curves for Al-4.0wt%Si-2.5wt%Cu-0.5wt%Mg alloys heat treated during 0, 30, 90 and 210s holding times at: a) 45% and b) 60% of solid fraction.

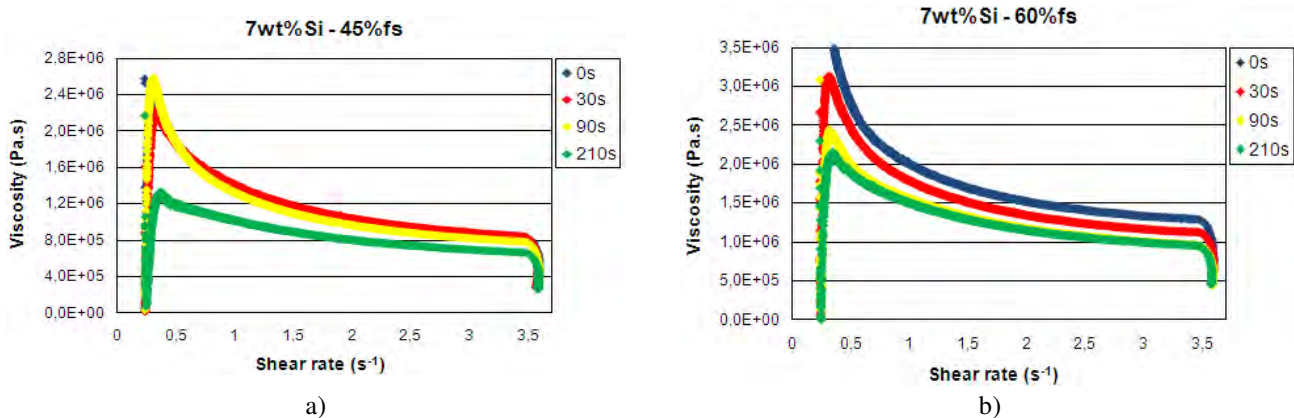


Figure 4. Viscosity *versus* shear rate curves for Al-7.0wt%Si-2.5wt%Cu-0.5wt%Mg alloys heat treated during 0, 30, 90 and 210s holding times at: a) 45% and b) 60% of solid fraction.

According to Kang *et al.* (1999) in the compression experiments of SSM, macro separation appeared between the solid and the liquid region because of the outflow of the liquid state and densification of the structure was observed in the middle of part. After the solid phase is deformed initially around the die, the component of liquid region gradually flows to the surface with critical strain rate. At this time, the liquid region of the surface outflows to the surface of the material, and solid grains and liquid phase flow simultaneously so that the stress is reduced. The stress increases continuously with an ongoing deformation only for the solid region around the die. This phenomenon is caused by the fast occurrence of solidification because temperature of SSM is lower than the initial temperature around die through heat transfer.

Peaks with the top in order to 0.25 of shear rate, i.e., initial stages of compression, observed in all curves from Fig. 1 to 4 are inherent to SSM compression experiments. They occur due to a three-dimensional network of solid globular particles distributed at whole sample from which the semi-solid sample supports its own weight and can be handled as a solid – this skeleton promotes the initial resistance to compression (Atkinson, 2005). Alloys with 60% of solid fraction have initial peaks much more pronounced than those with 45% of solid fraction due to higher concentration of solid phase, and therefore, a skeleton of solid particles much more dense and complex, generating higher resistance to flow at the beginning of compression.

An important characteristic observed for all viscosity *versus* shear rate curves is the quasi-constant level at which the viscosity remains the same while shear rate increased, especially between 1.0 and 3.0s⁻¹ of shear. At this level the material behaves as a newtonian fluid and its viscosity keeps constant even with varying shear rate – such phenomenon has already been reported by Zoqui (2001), who noted that how higher the globular character of semi-solid material, smaller the drop of apparent viscosity at the increasing of shear rate.

Apparent viscosity was adopted considering average values for each curve, measured between 1.0 and 3.0s⁻¹ of shear for apparent viscosity *versus* shear rate curves. Tab. 3 presents apparent viscosity for all analyzed condition.

Table 3. Apparent viscosity for all analyzed alloys.

Alloy	Solid fraction (%)	Holding time (s)	Apparent viscosity (10 ⁵ Pa.s)
Al-1.0wt%Si-2.5wt%Cu-0.5wt%Mg	45	0	2.50
		30	2.15
		90	2.12
		210	1.46
	60	0	3.96
		30	3.35
		90	2.68
		210	2.36
Al-2.0wt%Si-2.5wt%Cu-0.5wt%Mg	45	0	2.05
		30	1.96
		90	1.31
		210	1.57
	60	0	3.25
		30	2.91
		90	2.29
		210	1.66
Al-4.0wt%Si-2.5wt%Cu-0.5wt%Mg	45	0	1.72
		30	1.39
		90	1.45
		210	1.16
	60	0	2.87
		30	2.38
		90	2.02
		210	1.42
Al-7.0wt%Si-2.5wt%Cu-0.5wt%Mg	45	0	11.31
		30	10.71
		90	11.00
		210	8.53
	60	0	16.66
		30	14.74
		90	15.18
		210	12.41

Apparent viscosity clearly decreases with increasing of silicon content from 1 to 4wt%Si; 4wt%Si presented in some cases apparent viscosity in order to 50% lower than 1 and 2wt%Si alloys. Apparent viscosity also decreases with the decreasing of fraction solid. This behavior shows that increasing silicon content up to 4wt% and set solid fraction at 45% results in decreasing apparent viscosity due to a primordial factor: more eutectic contents (with minus solid particles) that possibly better lubrication among solid particles during semi-solid processing.

When holding time is increased from 0 to 210s favorable semi-solid behaviors are promoted due to better globularization conditions (Zoqui, 2001). Higher solid fraction caused higher apparent viscosity levels by the same ways discussed before – less liquid and then worse lubrication among these solid particles. The exception is 2wt%Si

heat treated at 210s for 45%fs which presented increases in order to 30% when compared to 90s of holding time – coalescence effects associated with long holding time of 210s were responsible for grain growth which generated the raise of strain for these alloys at this particular condition.

7wt%Si alloys presented worst performance of ever probably due to dendritic microstructures that promote considerable raises for both strain and viscosity – in the case of apparent viscosity, presented levels till ten times higher than the other alloys. Moreover, it is important to say that any apparent viscosity level reached for 1, 2 and 4wt%Si alloys was bigger than 5.10^5 Pa.s, what according Flemings (1991) is equivalent to glass working range, i.e., very low levels.

Figures 1 to 4 and Tab. 3 show that silicon content is, in fact, the most relevant variable on the apparent viscosity performance. 1, 2 and 4wt%Si alloys presented apparent viscosity at similar levels of about 1.5 to 3.10^5 Pa.s while 7wt%Si alloy present apparent viscosity almost five times bigger or more with levels of about 12.10^5 Pa.s.

Solid fraction acts increasing viscosity levels from 45 to 60% due to more solid-solid contact during semi-solid processing and the increasing of holding time from 0 to 210s led to lower viscosity levels.

Solid fraction and holding time presented the same behavior observed for strain analyses, with best performances reached for 45%fs and 210s of holding times due to the same reasons. It is clear the influence of silicon content and solid fraction on the performance of alloys in terms of apparent viscosity as well as the influence of higher holding times due to better morphological features reached primordially by means of *Ostwald* ripening and coalescence phenomena, both dependent of holding time at high temperatures, during the morphological evolution of these alloys in the proposed test conditions (Loué and Suéry, 1995; Gang Wan and Sahm, 1990; Guo *et al.*, 2010).

4. CONCLUSIONS

Thixoformability of new Al–1.0wt%Si–2.5wt%Cu–0.5wt%Mg, Al–2.0wt%Si–2.5wt%Cu–0.5wt%Mg, Al–4.0wt%Si–2.5wt%Cu–0.5wt%Mg and Al–7.0wt%Si–2.5wt%Cu–0.5wt%Mg alloys produced by ultra-refining by addition of Al–5.0wt%Ti–1.0wt%B master alloy was evaluated and the main conclusions are:

- Apparent viscosity decreases with the increasing of silicon content and with the decreasing of fraction solid. Increasing silicon content up to 4wt% and set solid fraction at 45% results in decreasing apparent viscosity due a primordial factor: more eutectic contents (with minus solid particles) that possibly better lubrication among solid particles during semi-solid processing;
- 7wt%Si alloys presented worst performance of ever, with viscosity levels till ten times higher than the other alloys;
- It was evident that a good semi-solid behavior during thixoforming mostly depends on silicon contents. The best condition was found for 4wt%Si alloy that presented best combination among several analyzed parameters;
- 1, 2 and 4wt%Si alloys were considered very suitable for thixoforming processes presenting apparent viscosity of about 5.10^5 Pa.s, equivalent to glass working range.

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6. REFERENCES

- Atkinson, H.V., 2005. “Modelling the semisolid processing of metallic alloys”. *Progress in Materials Science*, Vol. 50, p. 341-412.
- Chiarmetta, G., 2000. In *Proceedings of the 6th International Conference on Semi-solid Processing of Alloys and Composites*. Turin, Italy.
- Flemings, M.C., 1991. “Behaviour of metal alloys in the semi-solid state”. *Metallurgical Transactions A*, Vol. 22A, p. 957-981.
- Flemings, M.C.; Riek, R.G.; Young, K.P., 1976. “Rheocasting”. *Materials Science and Engineering*, Vol. 25, p. 103-117.
- Gang Wan; Sahm, P.R., 1990. “Ostwald ripening in the isothermal rheocasting process”. *Acta Metallurgica et Materialia*, Vol. 38, p. 967-972.
- Guo, H.M.; Luo, X.Q.; Zhang, A.S.; Yang, X.J., 2010. “Isothermal coarsening of primary particles during rheocasting”. *Transactions of Nonferrous Metals Society of China*, Vol. 20, p. 1361-1366.
- Kang, C.G.; Choi, J.S.; Kim, K.H., 1999. “The Effect of Strain Rate on Macroscopic Behaviour in the Compression Forming of Semi-solid Aluminium Alloy”. *Journal of Materials Processing Technology*, Vol. 88, p. 159-168.
- Kirkwood, D.H., 2001. “Semisolid processing”. *Encyclopedia of Materials: Science and Technology*, p. 8432-8437.
- Kirkwood, D.H., 1994. “Semi-solid metal processing”. *International Materials Reviews*, Vol. 39, p. 173-189.

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- Laxmanan, V.; Flemings, M.C., 1980. "Deformation of semi-solid Sn-15pct Pb alloy". *Metallurgical Transactions A*, Vol. 11A, p. 1927-1937.
- Loué, W.R.; Suéry, M., 1995. "Microstructural evolution during partial remelting of Al-Si-7Mg alloys". *Materials Science and Engineering A*, Vol. 203, p. 1-13.
- Rosso, M., 2012. "Thixocasting and rheocasting technologies, improvements going on". *Journal of Achievements in Materials and Manufacturing Engineering*, Vol. 54/1, p. 110-119.
- Spencer, D.B.; Mehrabian, R.; Flemings, M.C., 1972. "Rheological behaviour of Sn-15t%Pb in the crystallization range". *Metallurgical Transactions*, Vol. 3, p. 1925-1932.
- Zoqui, E.J., 2001. "Obtenção e Caracterização de Ligas Al-Si Reofundidas". Campinas, Faculdade de Engenharia Mecânica, Universidade Estadual de Campinas, 192p. Tese (Livre Docência).

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