Optimization and Utilization of Semisolid Casting Process for Semisolid Welding of Al-6061 Alloy

M. Hajihashemi*[a], M. Shamanian[b], B. Niroumand[c]

[a]*MSc Student, Department of Materials Engineering, Isfahan University of Technology, Isfahan, Iran.*
[b]*Full Professor, Department of Materials Engineering, Isfahan University of Technology, Isfahan, Iran.*
[c]*Associate Professor, Department of Materials Engineering, Isfahan University of Technology, Isfahan, Iran.*

ARTICLE INFO

Article history:

Received 13 Aug 2012
Accepted 24 Nov 2012
Available online 20 November 2013

Keywords:

Al6061 alloy
Semisolid processing
Cooling slope
Sphericity
Semisolid welding.

ABSTRACT

Semisolid processing is one of the modern routes in sound and near net shape parts production. Preparation of semisolid slurry using a cooling slope is increasingly becoming popular, primarily because of its simplicity in design and ease of control of the process. In this research, the microstructures of Al6061 semisolid alloy cast via a miniature cooling slope were investigated. The properties of final microstructures such as sphericity depend on such casting factors as pouring rate, superheat, slope angle and slope length. In this work, the relationships between the process parameters and microstructural properties of semisolid castings were identified using a two level factorial design. The results showed that simultaneous increase or decrease in pouring rate and cooling slope length can result in the most proper microstructure. The optimum result was then successfully used for semisolid welding of the alloy.

1. Introduction

6061 aluminum alloy is one of the most commonly used alloys in structurally demanding tasks that require corrosion resistance and good strength such as marine transport parts, rail vehicles, office supplies, tanks fittings, high pressure applications and wires and pipelines [1]. Many of these applications depend on various mechanical properties that make the study of the microstructural behavior of these alloys in the welding inevitable.

In many of the common methods of welding where incorporation and penetration of the base metal is effective (such as various types of arc welding, electron beam welding, laser welding) [2-3], and includes local heating up to liquidus temperature, the molten metal is generally frozen with a dendritic micro–structure. From metallurgical standpoint, this could lead to creation of porosity, impurities and inappropriate and uncontrolled orientation of the grains which decrease the welding properties.

Metal joining using semi-solid metal slurries as filler (semisolid metal joining) can avoid many of the problems mentioned in the liquid phase welding. This slurry, which can be like the base metal, flows across the preheated groove and experiences different freezing and heat transfer conditions compared to those of the usual methods of welding.

The weld microstructure obtained from this method is always equiaxed and freezing will begin simultaneously from all the primary solid particles in the slurry.

Corresponding author:
E-mail address: M.hajihashemi@ma.iut.ac.ir (Mehdi Hajihashemi).

Other benefits of this method include absence of spattering and welding smokes.

Recently, semi-solid metal processing has become one of the very important methods to make appropriate microstructural properties. The basic idea of the semi-solid processing of metals, developed in 1972 at the Massachusetts Institute of Technology USA, included creating turbulence in an alloy during its solidification for producing a slurry of spherical primary particles in a molten matrix [4]. During agitation in the semi-solid state, dendritic microstructure arising from high cooling rate in the early moments of freezing is fragmented and makes a semi-solid slurry containing solid particles in a molten matrix. In this case, metal shows thixotropic behavior meaning that the viscosity is a function of the applied shear stress and time. It reveals itself by the occurrence of hysteresis loops in the shear stress–shear rate diagram, when the shear rate is decreased to zero and increased again to its initial value after a given resting time. Because the spherical particles in a semi-solid slurry tend to agglomerate, the viscosity increases with increasing time. If the slurry is subjected to stresses, the agglomerated particles are broken down and the viscosity drops [4]. The important benefits of this process compared to common methods of casting, include lower temperature ranges than the molten metal and reduction in thermal energy consumption, viscose behavior of the material when it flows into the mold and reducing the amount of gas cavities and gas solubility, reduced shrinkages during solidification, increasing the lifetime of the mold and the improvement of mechanical properties [4-7].This process will be very convenient for producing large volumes of die cast parts, including light-weight and high strength components used in the automotive and electronics industries. In addition, this method has been practiced with low solid fraction gravity casting in the mould [8]. In recent years, a family of processes has been developed for producing semi-solid slurries using copious nucleation associated with low super heat casting processes such as cooling slope and low super heat casting are among these methods [4].

In the cooling slope method, semi-solid slurry is made with the smooth flow of the slightly superheated melt on a cooling slope followed by complete solidification in a mould. Many researchers believe that seed crystals starts to nucleate and grow on the wall of the slope and are then swept from the walls. In this mode, the melt consists of a large number of these small crystal nuclei that solidify within the mould and lead to production of a fine and non-dendritic microstructure [9]. Under the effect of the applied stresses caused by the actions of colliding with the surface of the slope and flowing on it, the microstructural transfer from dendritic to almost spherical occurs. Because of the slurry flow, melting and deformation of dendritic arms occur and lead to crystal multiplication [10] which increases the final grain density. Accordingly, the process of semi-solid casting using the cooling slope is attractive due to the simplicity of the design and ease of control of the process. However, selecting the appropriate levels of the effect of different factors on semi-solid casting via cooling slope to achieve the suitable subsequent properties are very important.

The use of semi-solid slurries for welding was first used by Mendez et al. in 2002 for welding of a Sn-Pb alloy [11]. The key factors pointed out in this study were the slope and slurry temperatures. By studying the heat transfer, dimensional analysis, changes in viscosity and deposit rate of the Sn-5% Pb slurry in the groove space of the weld they determined the optimum temperature of the slope and the slurry to achieve the best results, including microstructural control of the weld, less residual stresses and smaller heat-affected zone.

In the present research, a miniature cooling slope which permits the use of very low superheat and flow rates, was built and used for the first time to study the effects of important cooling slope processing parameters on the microstructure of semisolid cast Al6061 alloy using design of experiment (DOE) method. The resulted optimized microstructure was then used for semi-solid welding.

2. Experimental Procedure

In this research, commercial 6061 aluminum alloy was used as a billet to produce semi-solid slurry by a miniature scale cooling slope and as a sheet with a thickness of 6 mm for the welding. Chemical compositions of both are reported in Table 1. Figure 1 shows the schematic of the setup built and used in this study. This slope is very small (for casting small parts and attachment to other methods such as semi-solid welding), and is made of mild steel St 37, and is cooled by a number of spiral water-circulated pipes. Water-circulation conditions, the number of pipes, the incoming water temperature and the way to let the water flow in the substrate were designed in such a way that the cooling system was able to quite cool the miniature slope. Meanwhile, to prevent sticking and direct contact of the molten metal with the slope, the surface was coated by Boron Nitride.

Table1. Chemical composition of commercial 6061 aluminum alloy used for welding (sheet) and casting (billet)

	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Ni
Billet	Balance	0.563	0.646	0.289	0.068	0.884	0.194	0.089	0.015	< 0.020
Sheet	Balance	0.475	0.529	0.233	0.091	0.830	0.199	0.089	< 0.010	< 0.020

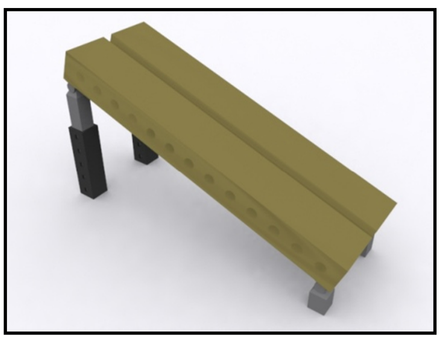

Fig.1. Schematic view of the miniature cooling slope

2-1- Characterization

Preparation of samples for image analysis was performed with the use of optical microscope after grounding, electro-polishing and electro-etching. Prior to electro-polishing, the samples were ground with 600-grit abrasive paper. The electrolyte solution used consisted of 800 ml ethanol, 140 ml of distilled water and 60 ml of $HClO_4$ and was employed at voltages of 60 and 6-Volts for electro-polishing (held for 15 seconds) and electro-etching (held for 5 seconds), respectively. The temperature of the process of electro-etching was equal to -30ºC.

In order to measure the grain size and sphericity, microscopic images analysis was carried out by Clemex Vision PE Litee/3.5 software. Prior to analysis, the images were edited in order to increase the accuracy of the measurements.

2-2- Sample preparation for welding

For preparation of welding samples, 6061-T6 aluminum alloy sheets of 20*10*6 cm^3 dimensions were used. Figure 2 shows the placement of the sheets and the angle of the welding grooves. In order to remove the oxide layer, the specimens were completely brushed and rinsed with acetone before welding. Before welding, the samples were preheated to 450ºC using an electrical resistance heater.

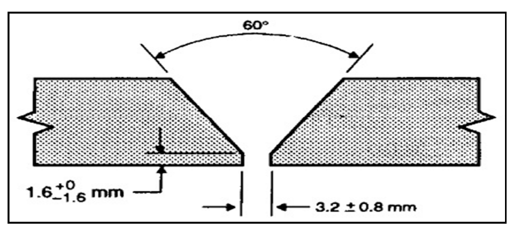

Fig.2. Schematic view of the sheets arrangement during the welding

2-3- Design of experiment

In an experiment, one or more of the process variables (or Factors) must be deliberately changed to determine the effect of the applied changes on the response variables. The (statistical) design of experiments (*DOE*) is an efficient procedure for planning experiments so that the data obtained can be analyzed to yield valid and optimal conclusions. The choice of a design of experiment depends on the objectives of the experiment and the number of factors to be investigated [12].

In order to determine the optimum conditions and the influence of main cooling slope, casting parameters such as flow rate, surface angle, slope length and melt superheat on the microstructural properties of final parts, a two level (low and high) factorial design including three center points was chosen to improve the precision of the model and curvature investigation. The design is shown in Table 2. These center points were added to the design to investigate the reproducibility, random error of the experiments [12], and nonlinearity and to provide additional degrees of freedom for the estimation of error variance. 2^n factorial design is the simplest type of factorial design as it uses two levels and thereby reduces the number of experimental conditions.

Other different experimental designs such as fractional factorial and Taguchi orthogonal array exclude some of the factor-levels from the full-factorial design to achieve an optimized combination with minimum time and computational cost compared to the full-factorial method. Although the full factorial design requires a large number of expensive experiments and calculations, it offers more precise results concerning the interactions between factors and avoids loss of information and further erroneous conclusions.

The experiments were performed in random order to ensure that uncontrolled factors did not influence the results [12]. Design and statistical analysis of the experiments was done by Design-Expert 7 (State-Ease, Inc.) software.

2-4- Hardness and tensile strength tests

To study the hardness changes in different areas of the semi-solid cast and welded specimens, Vickers microhardness test device BUEHLER MICROMET 5101 with a force of 50 g was used. The reported hardness values are averages of at least seven tests. With regard to the significance of the heat affected zone, the hardness profiles also covered this region. Also, to investigate the tensile strength of the joined sheets, the samples were strained by a 25 ton HOUNSFIELD H25KS machine at 1.5 mm/min cross head speed. Figure 3 shows the overall dimensions of the tensile test specimens [13].

Table2. Design of experiments: actual design.

Std	Run	Factor A Superheat (^{0}C)	Factor B* Casting rate (gr/cm^3)	Factor C Surface Length (cm)	Factor D Surface Angle (Degree)
8	1	30.00	3.00	30.00	40.00
15	2	10.00	3.00	30.00	60.00
3	3	10.00	3.00	5.00	40.00
11	4	10.00	3.00	5.00	60.00
19	5	20.00	2.00	17.50	50.00
17	6	20.00	2.00	17.50	50.00
7	7	10.00	3.00	30.00	40.00
4	8	30.00	3.00	5.00	40.00
14	9	30.00	1.00	30.00	60.00
10	10	30.00	1.00	5.00	60.00
6	11	30.00	1.00	30.00	40.00
13	12	10.00	1.00	30.00	60.00
16	13	30.00	3.00	30.00	60.00
1	14	10.00	1.00	5.00	40.00
5	15	10.00	1.00	30.00	40.00
18	16	20.00	2.00	17.50	50.00
12	17	30.00	3.00	5.00	60.00
9	18	10.00	1.00	5.00	60.00
2	19	30.00	1.00	5.00	40.00

*This factor is reported in coded values. Codes 1, 2 and 3 represent 1.2, 2 and 4 ml/s, respectively.

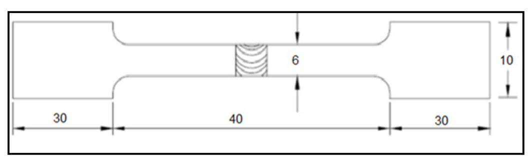

Fig. 3. Schematic of the tensile test specimens

3- Results and discussion

3-1- Semi-solid slurry

Based on the list of the effective parameters in the maximum sphericity model obtained from the optimization experiments, which have been shown in Table 3, the greatest impacts are associated with the interaction between the cooling slope length and the pouring rate factors (BC), the cooling slope length (C), interaction between the superheat, pouring rate and the cooling slope length factors

(ABC), pouring rate of the casting (B), the cooling slope angle (D), the interaction between the cooling slope length and superheat factors (AC) and the interaction between the superheat and pouring rate factors (AB). The sum of squares represents the amount of deviation from the average as a result of the effect of the corresponding parameter. Fig 4 shows the normal plot of the factors in the model. This chart can be used to extract the important parameters. The points contained in this chart are an estimation of all of the factors in the model, which also includes the possible interactions. The factors that have little effect on the model are estimated to be in the normal distribution. Also, important effects (parameters) show up as outliers on the normal probability plot [12]. So, more distance to the straight line is equal to greater effect on the model. Remarkable thing is the complete similarity of the effect of D factor (the cooling slope angle) and the interaction between the cooling slope length and the superheat factors (AC).It implies that by changing the amount of factors C and A, D-factor can be ignored. More investigation into the most effective factor in the model will follow.

Table3. Parameters affecting maximum sphericity model

Factor	Sum of squares	Contribution
B: Pouring rate	3.21	7.03
C: cooling slope length	10.28	22.51
D: Cooling slope angle	2.14	4.68
AB	0.98	2.15
AC	2.14	4.68
BC	18	39.42
ABC	7.74	16.94

3-2- BC interaction factor

This factor which is the most effective for maximum sphericity model consists of interaction of cooling slope length with pouring rate. Based on the contour plot of the BC interaction (Fig. 5), it is observed that the amount of sphericity is maximized in two areas of the graph (red areas). The first point is at the lowest pouring rate and the least cooling slope length (rate 1 and 5 cm length, respectively). Because the superheat temperatures are chosen at a very low level (10-30°C, this plot is drawn in 10ºC superheat and cooling slope angle of 40º), an increase of the slope length will increase the amount of the solidified melt on the slope surface. Moreover, the cooling slope does not act well enough because of the occurrence of the main semisolid processing phenomenon in the initial parts of the slope. Therefore, it can be claimed that the melt reached to the end of the slope came into less contact with the slope and slid just on the solidified melt. Increase of pouring rate (rate 3) and cooling slope length (30 cm) increase the sphericity to the second maximum amount. Its reason can be the fast flow of the melt on the slope, and thus, reduced melt freezing on the surface due to the higher casting rate. Because of this, in addition to the increase of stresses imposed on the melt due to high pouring rate, molten metal moves in a longer path on the cooling slope. This leads to more fragmentation of growing nuclei which are transforming to dendrites (due to fast cooling) and sphericity increase [9]. It seems that by an increase of casting rates (rate 3) and decrease in the cooling slope length (5cm), the slope does not act well enough and the melt exit the slope before completing the fragmentation of dendrites. Fig 6 shows the desirability of BC interaction on maximum sphericity model. The desirability shows how the sample is near the goal and varies in the range of 0-1. The closer this number to zero, the more undesirable and closer to one, the more desirable the model [12]. According to this explanation, the “desirability” changes, as the model behavior does, with simultaneous interaction of B and C and its maximum occurs in the maximum areas of Figure 6.

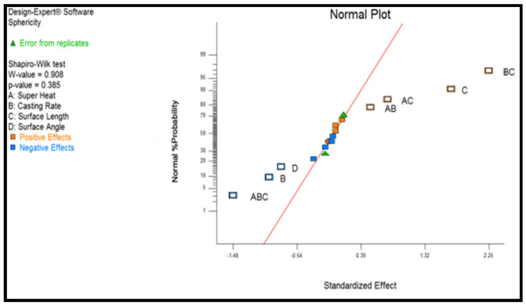

Fig.4. Normal plot of effective factors in maximum sphericity

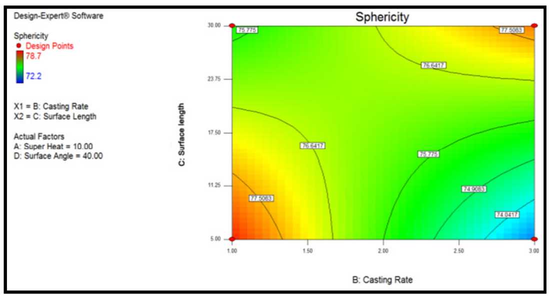

Fig.5. Contour of BC interaction in real maximum sphericity

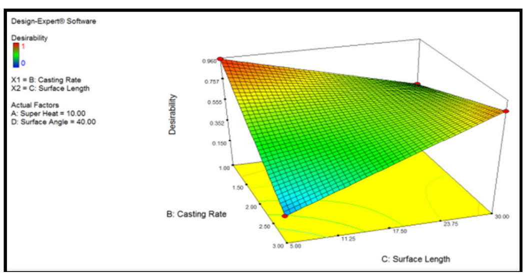

Fig.6. 3D desirability diagram of BC interaction factor in maximum sphericity model

Figure 7 indicates the graph of calculated sphericity versus the measured sphericity. As it shows, the data have very little dispersion off the line with slope of 1. Thus it can be claimed that the achieved mathematical model for the sphericity response has the adequate precision. Equation 1 is the relationship of sphericity versus the input factors of the software:

$$\text{Sphericity} = 75.85 - 0.48B + 0.85C - 0.39D + 0.26AB + 0.39AC + 1.13BC - 0.74ABC \quad (1)$$

Superheat values up to 10°C, the pouring rate of 1, cooling slope length of 5 cm and slope angle of 40° would lead to the maximum amount of sphericity (about 78.37).

3-3- Semi-solid welding of6061aluminum alloy

Figure 8 represents the microstructural changes in the semi-solid welded sample. As it is obvious, noticeable changes in the size and shape of the grains have occurred with moving from the heat affected zone (Figure 8a) to the weld zone (Figure 8b). The main cause of this can be associated with the use of semi-solid slurry with appropriate microstructural characteristics. However, compared to the mentioned structures in previous sections, noticeable grain growth has happened. The main cause of this can be due to preheat of the base metal during the welding. In this way, and with the decrease in cooling rate, some opportunity for grain growth may be provided before complete solidification.

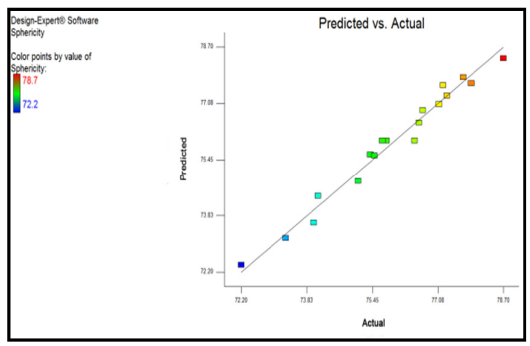

Fig.7. Diagram of predicted vs. actual terms in sphericity model

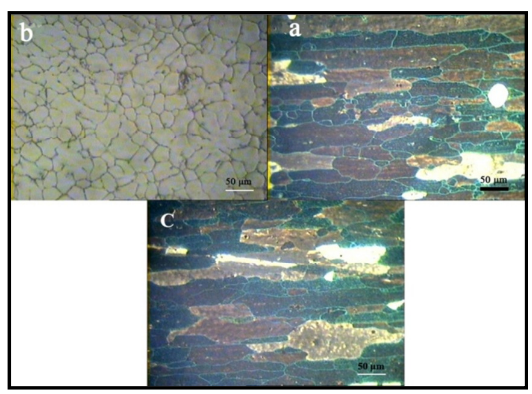

Fig.8. Microstructures of the semisolid joints in a) HAZ and b) weld zone and c) base metal

Figure 9 represents the Vickers hardness and corresponding macro images of transverse cross section area of the weld zone (after the tensile test). As this Figure shows, the heat-affected zone (HAZ) has the lowest hardness values. By moving away from HAZ, hardness values have approached to those of the base metal. The weld zone hardness is relatively higher than the HAZ. This can be attributed to the fine spherical microstructure of this zone.

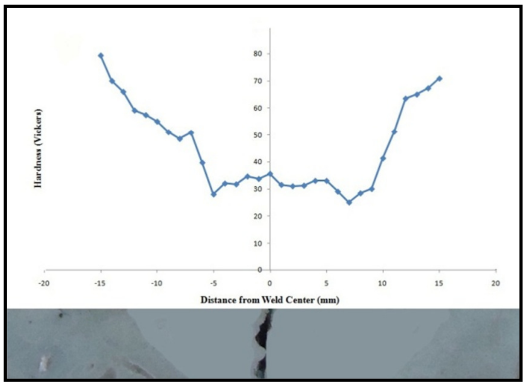

Fig.9. Hardness across the cross section of semisolid welded joints (macrograph of the joint after tensile test is also shown.)

Figure 10 shows the ultimate tensile strength (UTS), yield strength (YS) and elongation of the Al6061 alloy (Figure 10a) and semi-solid welded parts (Figure 10b). The yield strength of the samples was determined by the Offset method. The ultimate tensile strength, yield strength and elongationofAl-6061 alloy semi-solid welded samples are 37.5, 114 MP and 2.4%, respectively. These values are equal to 65, 347 MP and 18.5% for unwelded samples. Cause of reduction of mechanical properties in semi-solid welded samples can be related to the complete elimination of precipitates in the weld zone and the presence of very large heat affected zone due to preheat of the base metal (450°C). This may cause the growth and even dissolution of the existing precipitates in the structure. Furthermore, factors such as lack of fusion and insufficient integration of sample surfaces with the semi-solid slurry as well as poor wettability of these two surfaces due to the presence of oxide layers on the joint surfaces can be other factors that affect the deterioration of the properties.

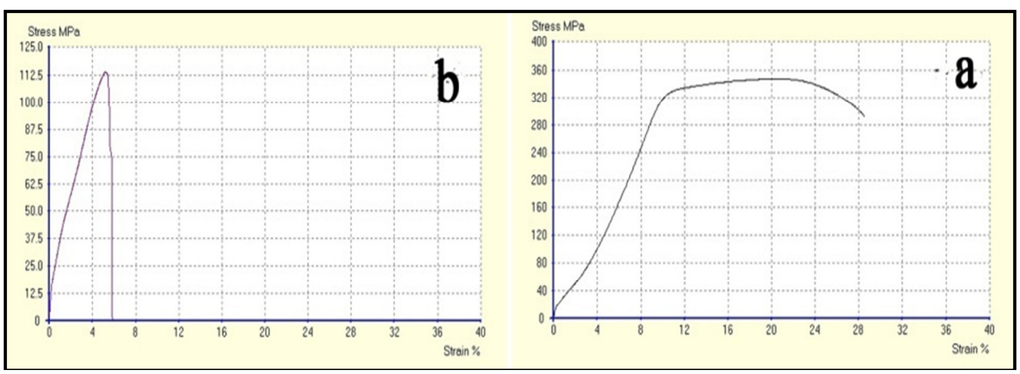

Fig.10. Strain-stress diagram of a) non-welded and b) semisolid welded samples

4- Conclusion

In this work, a miniature cooling slope was successfully used for the first time to achieve globular microstructure of Al6061 alloy. Use of two-level factorial method to optimize the experiments and find the relationship between the factors and responses showed that the interaction between the cooling slope length and the pouring rate factors (BC)with contribution percent of 42/39%,has the greatest effect on the sphericity of microstructure resulting from the use of the miniature cooling slope. The results showed that when this factor is positive (simultaneous decrease or increase of B and C factors), sphericity increases. According to the mathematical model presented in Eq. 1, it can be claimed that the best microstructure in terms of the amount of sphericity (numeric value of about 78.37) can be achieved at 10°C superheat, pouring rate of 1, cooling slope length of 5 cm and slope angle of 40°. Moreover, using this optimal microstructure in semi-solid welding of Al6061 alloy will improve the properties of the weld zone.

References

[1] T. Kvačkaj, R. Bidulský, “Aluminium alloys, Theory and applications”, India, InTech, 2011.
[2] American Welding Society, Welding Handbook, Vol. 2, Welding Processes, 8th Edition, USA, 1991.
[3] American Society for Metals, Metals Handbook, Vol. 6. Welding, Brazing and Soldering, 9th Edition, USA, 1983.
[4] D. H. Kirkwood, M. Suery, P. Kapranos, H. V. Atkinson and K. P. Young, “Semisolid Processing of alloys”, London, Springer Series in Materials Science,2010.
[5] T. Haga, R. Nakamura, R. Tago and H. Watar, “Effects of casting factors of cooling slope on semisolid condition”, Transactions of Nonferrous Metals Society of China, 20, 2010,pp s968-s972.
[6] E. Tzimas and A. Zavaliangos, “Evaluation of volume fraction of solid in alloys formed by semisolid processing”, Journal of Materials Science, 35, 2000,pp 5319–5329.
[7] J. Wannasin and S. Thanabumrungkul, “Development of a semi-solid metal processing technique for aluminium casting applications”, Songklanakarin Journal of Science and Technology, 30, 2008,pp 215–220.
[8] J. Yurko, A. Martinez and M. Flemings, “SSR™: The Spheroidal Growth Route to Semi-Solid Forming”, Proceedings of the 8th International Conference on Semi-Solid Processing of Alloys and Composites, Limassol, Cyprus, 2004,pp 21-23.
[9] G. Hirt and R. Kopp, “Thixoforming”, Germany, WILEY-VCH,2009.
[10] T.F. Bower and M.C. Flemings, “Formation of the Chill Zone in Ingot Solidification”, Transactions of the Metallurgical Society of AIME, 239, 1967, pp 216–219.
[11] P.F.Mendez, C.S. Rice, S.B. Brown, “Joining using semisolid metals”, Welding Journal, Vol. 81,2002, pp 181–187.
[12] D.C. Montgomery, “Design and analysis of experiments”, USA, John Wiely and Sons Inc, 2000.
[13] “Standard test methods for Tension Testing of Metallic Materials”, ASTM handbook, Vol. 3, E0008M–04, United States, 2004.