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Weibull analysis of fluidity and hardness of ultrasonically degassed secondary Al7Si0.3Mg aluminum alloy

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Abstract: The influence of ultrasonic degassing process on fluidity and hardness of secondary Al7Si0.3Mg alloy castings was studied by Weibull analysis. This work makes a contribution about fluidity and hardness distribution of secondary aluminum alloys with ultrasonic degassing phenomena using a two-parameter form of Weibull analysis. Results show that both hardness and fluidity of alloy are improved after the ultrasonic degassing process. Average efficiency of ultrasonic degassing on fluidity measurements is 31.71%, whereas on hardness values is 8.48%. The Brinell hardness of 45.7 and fluidity of 19.5 of Weibull modulus were achieved as the most reliable and reproducible after 45 s ultrasonic degassing process against 15 s and 30 s ultrasonic degassing processes. The value of 70.08 HB is obtained from ultrosonic degassing, which is equivalent to sand casting of primary Al7Si0.3Mg aluminum alloy, and the highest value of 56.4 cm for 45 s after ultrasonic degassing of fluidity was measured.

Key words: Weibull analysis; Weibull modulus; ultrasonic degassing; fluidity; hardness; aluminum

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In foundry engineering, casting parameters, such as fluidity and turbulent filling directly affect the properties of the cast metals, i.e. hardness and tensile strength. Predicting these parameters can improve the entire casting process. Also, it is necessary to establish these variables in simulation techniques, and casting procedures, i.e. fluidity test and mechanical test [1]. Dong et al. [2] have investigated the effect of ultrasonic stirring on hardness and concluded that if porosities were not eliminated, the hardness values of the materials could not be increased, even if average grain diameter and eutectic silicon aspect ratio are both lowered. Moussa et al. [3] has established ascending hardness values on Mg_5Si alloy being exposed to the ultrasonic degassing (UD) process with a 38% increase with regard to modification and refining of microstructural constituents. The variation of the mechanical properties of Al-Si alloys was investigated with solute addition and ultrasonic process. It is found that the solute addition has a great contribution to the hardness values of the alloy, and also the application of UD process to the same alloy yields an increment of 10% hardness values [4].

Fluidity is affected by some parameters, such as cross-section, superheat, alloy composition, viscosity, and grain refining. Colak et al. [5] studied Al7Si0.3Mg alloy to assess the effect of cross-section on the fluidity. They found that thin sections modified by Sr have a great effect on fluidity. Kwon and Lee [6] reported flow lengths of Al4.5Cu0.6Mn and Al7Si0.3Mg melts were improved from 20 mm to close to 100 mm with adding grain refiners, such as Ti and Al-Ti-B, at the same temperature.

It was reported that hydrogen is removed by ultrasonically cavitated bubbles and also, it has coupled effect on the bifilm removal utilized from their non-wettable surface by flotation [7]. This serviceable case takes effect on the fluidity of Al-Si-Mg melts. Eskin has specially studied this melt and observed that without any treatment, fluidity is measured as 500 mm, after Ar purging, it was 550 mm and after applying UD, fluidity was 670 mm [7-8]. Yu et al. [9] investigated preparing aluminum matrix surface composites (AMSC). They established that as the fluidity of the melt was increasing, the viscosity of the melt was decreasing in applying ultrasound.

Once these parameters are determined, it would be easy to characterize the parameters for standard manufacturing systems. Herein, Weibull [10] has

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introduced an empirical statistical distribution function, which could be implemented broadly to brittle materials such as metals and ceramics. Weibull distribution is one of the well-accepted statistical analyses to optimize and examine reliability, reproducibility, completeness, and cogency of any results [1-3]. Furthermore, the Weibull analysis is used to interpret casting properties (e.g. runner system design, the effect of bifilms, fatigue behavior) by different researchers [11-17]. For example, the geometry of the runner system has been optimized by Runyoro and Green using the Weibull analysis. Some other applications of the Weibull analysis are heat treatment [18] and centrifugal casting of alumina [19].

The two-parameter Weibull distribution is used to define any data set by:

$$P = 1 - exp[-\left(\frac{x}{H}\right)^m] \tag{1}$$

where P is the fraction of specimens that failed below or at a given characteristic value of x, H is the scale parameter or a characteristic value of x at which 62.8% of the population of specimens have failed and m is Weibull modulus or shape parameter [20-21]. For the evaluation of Weibull parameters, there are linear regression, method of moments, and maximum likelihood methods. Linear regression is the most popular one to apply. If the logarithm of Eq. (1) is taken, this procures as follows:

$$\ln[\ln(1\text{-}P)] = m\ln(x) - m\ln(H) \tag{2}$$

Then, Eq. (2) becomes a linear plot when ln(x) and ln(ln(1/(1-P)) are used. The slope is m (Weibull Modulus) and interception of $-m\ln(H)$ is the characteristic value [13]. Failure probability, P, is calculated by several assumptions in Ref. [22-24], but Kirtay and Dispinar [25] suggested that the Hazen estimation is the most stable method, and is determined by an estimator given in Eq. (3);

$$P = \frac{i - 0.5}{n} \tag{3}$$

where i is the rank in ascending order and n is total specimen number.

In this work, Hazen estimator for the failure probability was used to evaluate the Weibull analyses of hardness and fluidity test results with regard to different ultrasonic degassing durations (UD) of secondary aluminum alloy castings.

1 Experimental

A secondary Al7Si0.3Mg alloy of 5 kg was melted in a VULCAN 3-550 electric resistance furnace. The chemical composition of the alloy is given in Table 1. After holding 20 min at 740 °C, the melt was poured in a fluidity mould preheated to 250 °C to evaluate the effects of the ultrasonic degassing process on the alloy. The universal spiral fluidity mould is shown in Fig. 1.

Table 1: Chemical composition of secondary Al7Si0.3Mg alloy (wt.%)

Si	Mg	Fe	Ti	B	Ni	Sr	Al
7.28	0.227	0.07	0.11	0.003	0.004	0.013	Bal.

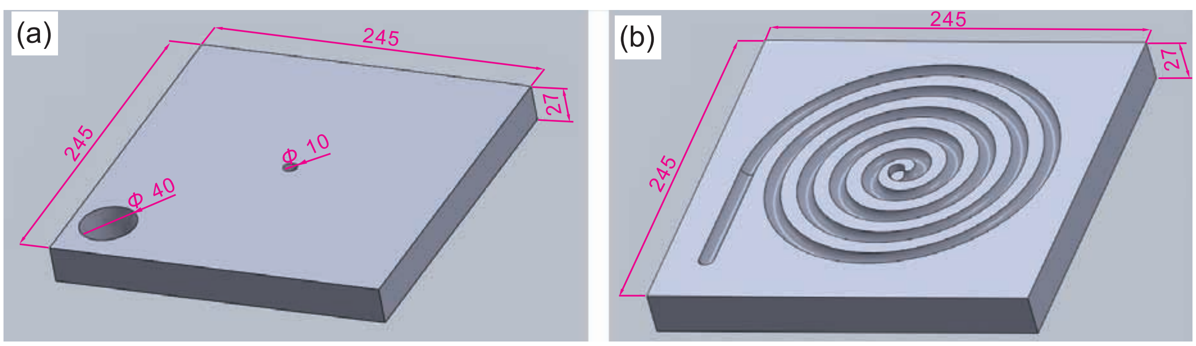

Fig. 1: Universal spiral fluidity test mould: (a) upper mould; (b) lower mould (unit: mm)

A constant ultrasonic frequency (19.8 kHz) was applied to the alloys using the RTUL ultrasonic degassing equipment. After pouring the reference specimen, the ultrasonic degassing process was carried out to the melt. Then, the spiral fluidity samples were produced. The ultrasonic duration was selected as 15, 30 and 45 s. The melt was poured after holding 10 min, producing 5 fluidity test specimens with UD.

Metallographic samples were cut from the end of the castings. Samples were ground and polished from 240 to 2,000 grit SiC abrasive papers. Microstructures of the specimens were revealed using a Nikon Eclipse MA100. Hardness measurements were conducted through Brinell Hardness following ASTM E10-18 standards; the hardness values were the average of ten measurements.

2 Results and discussion

2.1 Microstructure

Microstructures of ultrasonically degassed Al7Si0.3Mg aluminum alloy were given in Fig. 2 (a-c). As can be seen in the figures, the longer UD processing time leads to more refined grains and porosity-free structure. In Fig. 2 (a), after 15 s, it is obviously seen that there are some primary α-Al dendrite patterns. However, after 30 s, dendritic structures of

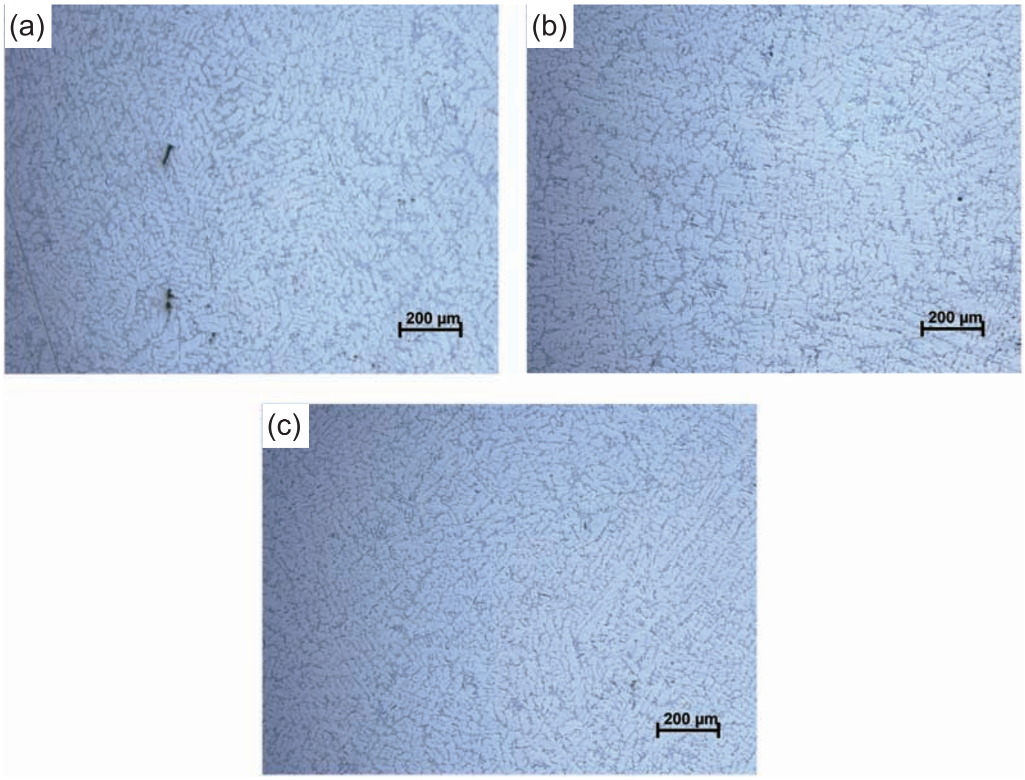

Fig. 2: Microstructures of ultrasonically degassed secondary aluminum alloy: (a) 15 s; (b) 30 s and; (c) 45 s

primary α-Al began to become non-dendritic morphology [Fig. 2(b)], and in 45 s, the primary α-Al dendrites became smaller in size and fibrous, and the microstructure also came in more immaculate and porosity-free [Fig. 2 (c)].

As shown in Fig. 2 (a-c), with increasing the UD processing time, the area fraction of primary α-Al phase and refining of primary α-Al dendrites increases; and decreasing bifilm and porosity-free castings could be obtained. It is reported that the UD process has a combined effect on nodulizing and minimizing of primary α-Al grains [18], degrading some of the harmful effects of intermetallics, i.e., β-Al_5FeSi, modifying the eutectic silicon, and also decreasing porosities and bifilms. Thus, decreased grain size of α-Al dendrite, and finely scattered secondary phases would result in the increase of hardness and fluidity of any alloy system [26-27].

2.2 Weibull distribution of Brinell hardness values

Figures 3–5 show the Weibull analyses of the secondary Al7Si0.3Mg aluminum alloy with regards to hardness values. In these figures, it is easily seen that ultrasonic degassing has a significant effect on hardness. In Fig. 3, Weibull modulus before UD is 12.5, while that after UD is 26.6. In addition, the regression coefficient values are 0.8385 and 0.9378 for that before and after the UD process, respectively. Similarly, in Fig. 4, the Weibull modulus is 12.5 before UD and 33.9 after UD. Also, the regression coefficient values are 0.915 and 0.9782 for that before and after UD, respectively. Finally, in Fig. 5 for 45 s ultrasonic degassing process values, the Weibull modulus is 13.3 before UD and 45.7 after UD. Regression coefficient value

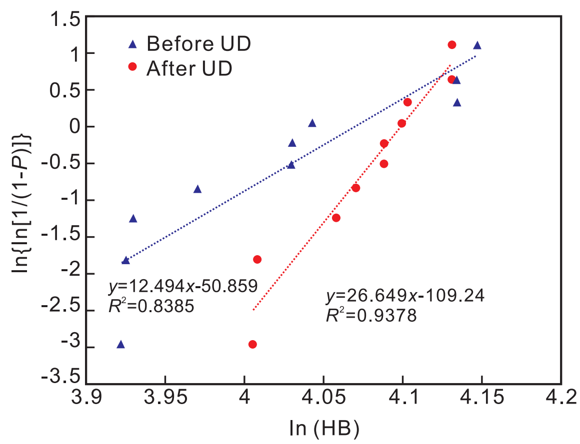

Fig. 3: Weibull analysis of 15 s ultrasonically degassed alloy versus Brinell hardness

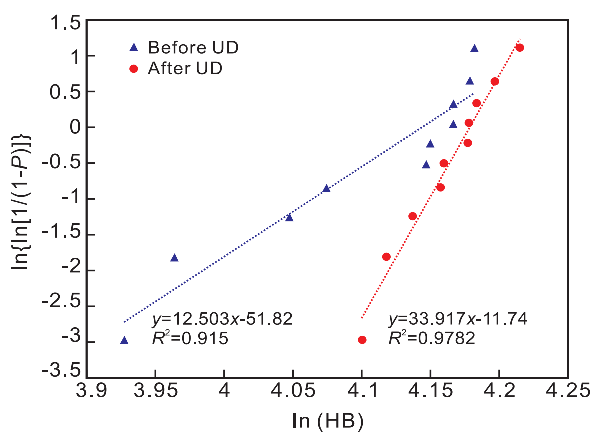

Fig. 4: Weibull analysis of 30 s ultrasonically degassed alloy versus Brinell hardness

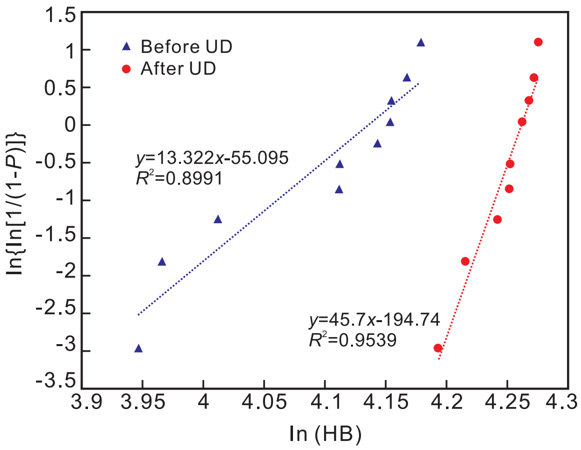

Fig. 5: Weibull analysis of 45 s ultrasonically degassed alloy versus Brinell hardness

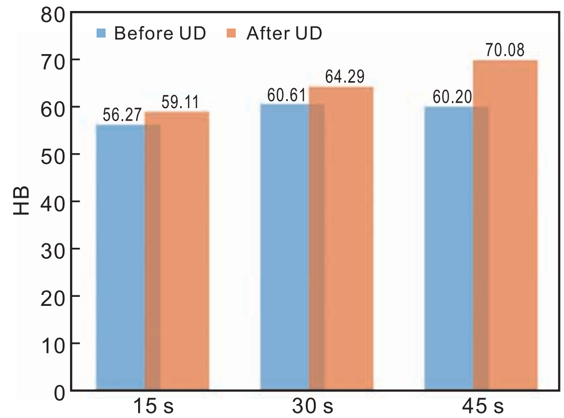

Fig. 6: Variation of Brinell hardness values before and after ultrasonic degassing (UD)

is 0.8991 for that before UD and 0.9539 for that after UD.

For all the test conditions, the hardness values increased after the UD process. Similar results were obtained by El-Aziz et al. [28]. They showed that the application of an ultrasonic process on $AlMg_5$ aids to increase hardness values from 67 to 75 HV. This is because a cavitation mechanism enables the formation of a great number of nuclei. Owing to this, during solidification, there could be few nucleation sites to form non-dendritic grains.

According to Campbell [29], for pressure die castings, Weibull modulus is often between 1 and 10, and for many gravity-filled castings, it could be between 10 and 30. For high-quality aerospace castings, Weibull modulus is expected to be between 50 and 100. The higher Weibull modulus indicated a narrower scattering of hardness values of different UD process durations. From this point of view, it could be considered that a Weibull modulus of 45.7 for 45 s UD process to the melt reveals the most reliable and reproducible result compared to those for 15 s and 30 s. With 33.9 of Weibull modulus, the second consistent option is 30 s UD process and with 26.6 of Weibull modulus, the last and the worst result is the 15 s UD process. This demonstrates that increasing the ultrasonic process time yields higher density, reduced porosity and bifilms, and enhanced fatigue behavior [30].

As can be seen in Fig. 6, although all melt characteristics are always different from each other as a first charge, namely before the UD process, all hardness values without an UD process are almost the same for this experimental work. Before the UD process, Brinell hardness values are 56.27 in 15 s, 60.61 in 30 s and 60.20 in 45 s. There is an obvious difference in the hardness of the alloys after degassing. These are 59.11 in 15 s, 64.29 in 30 s and 70.08 in 45 s. Also, considering the average hardness value of all experiments, before the UD process, it is 59.02 HB, whereas 64.49 HB is assigned after the UD process. From these values, it is determined that the UD process efficiency is about 8.48% for hardness. Also, if one would like to investigate the hardness recovery efficiency individually, it is easily seen that after 45 s UD process, there is an increase of 14.10%. At once, 30 s of ultrasonically degassed alloy has an efficiency of 5.88%, whereas this is 4.8% for 15 s. With 70.08 HB values, 45 s of ultrasonically degassed melt has the highest hardness value, that is equivalent to the sand casting of primary aluminum alloys. Thus, it is clearly seen that the UD process is effective to improve the hardness of the alloy.

2.3 Weibull distribution of fluidity

Since only one specimen was cast before the UD process, the Weibull analysis of secondary aluminum is assessed after ultrasonic degassing. This distribution is shown in Fig. 7. As can be seen, by UD, the fluidity of Al7Si0.3Mg is significantly increased with increased UD duration. In addition, the scatter of the results is decreased which resulted in more reliable and reproducible values. Davamiet al. [23] had the same findings of tensile strength and elongation on Weibull distribution of Al7Si0.3Mg alloy castings with three different casting combinations, including stirring and filtering. They demonstrated that the presenting of bifilms and using no filter in filling systems had a large scatter and was not reproducible, whereas bifilm-free and using a filter in a filling system had less scattering and a more reliable result.

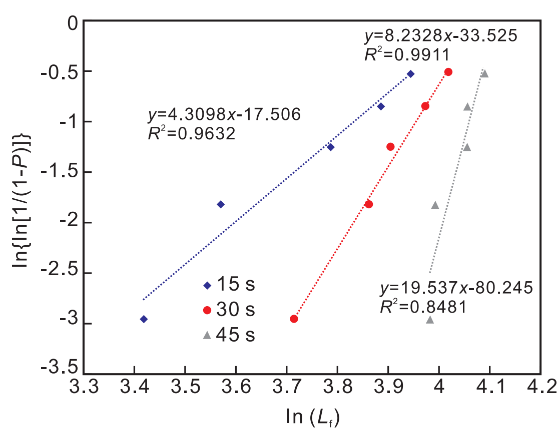

Fig. 7: Weibull distribution of fluidity with different ultrasonic degassing time

In Fig. 8, it is obviously seen that the fluidity values were enhanced via the UD process, as was hardness. The fluidity values for that before UD is measured as 30.33 and 37.5 cm, while 42, 49.3 and 56.4 cm for that after UD. The UD process

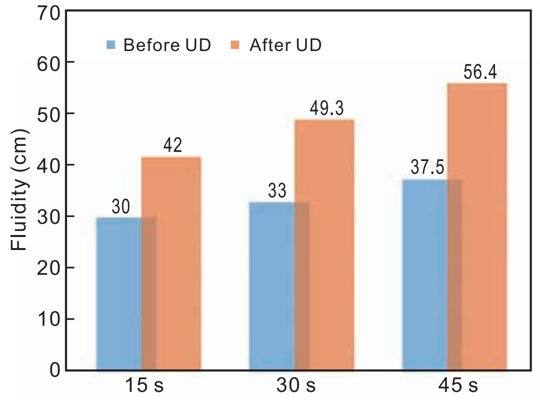

Fig. 8: Variation of fluidity before and after ultrasonic degassing (UD)

efficiently affected the fluidity values of alloys by about 32.97%. For 15 s, the increase of fluidity is 28.57% and the increases of the fluidity of 30 and 45 s are 33.06% and 33.51%, respectively. Thus, it is evident that the UD process is an effective way to improve fluidity values of alloys like hardness.

There is a good correlation between hardness and fluidity values of the alloys. As can be seen in Fig. 9, the UD processes also have an effect on hardness and fluidity in the same manner. After UD, both hardness and fluidity values are in the tendency to rise. It is obviously seen that the coefficient of regression after UD is considered reliable with a value of 0.9984, whereas it was just 0.5809. This low value means that melt quality is extremely variable with respect to first charge quality.

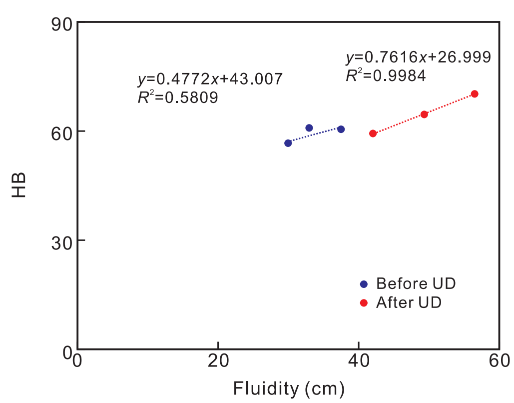

Fig. 9: Variation of fluidity versus Brinell hardness

2.4 Weibull Modulus

It was demonstrated from Refs. [5, 29, 31-33] that a decrease in Weibull modulus corresponds to a decrease in results in undesirable situations, whereas an increase in Weibull modulus accounts for favorable cases in the production of high-quality alloy castings. Higher Weibull modulus indicates higher average and lower scatter as in Figs. 10 and 11.

Variation of Weibull modulus versus ultrasonic degassing processing time for fluidity is given in Fig. 10. It is easily seen that 45 s UD processing time has the highest Weibull modulus average with 19.5, while 15 s UD has the worst with a value of 4.3. Thus, the most consistent, reliable, and reproducible one is 45 s UD with almost five times of 15 s UD for fluidity

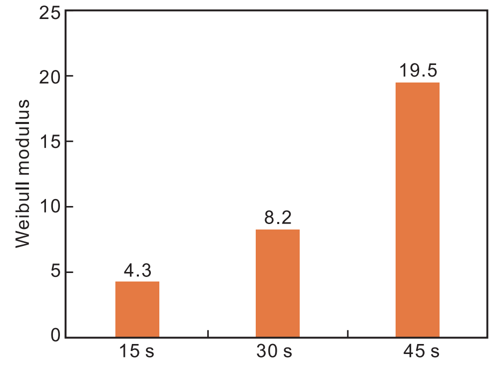

Fig. 10: Variation of Weibull modulus versus UD processing time for fluidity

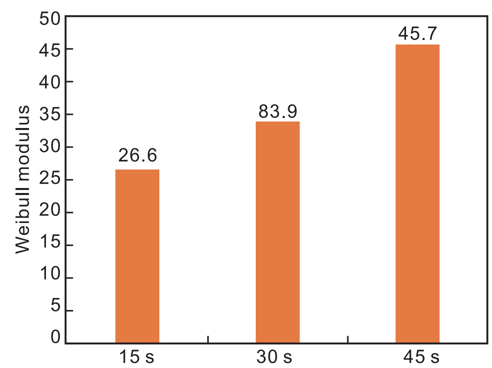

Fig. 11: Variation of Weibull modulus versus UD processing time for hardness

test results. Figure 11 shows Weibull modulus changing with respect to ultrasonic degassing time for hardness values. Again, 45 s UD processing period is the most reliable one for fluidity results. In this figure, 45 s UD with Weibull modulus of 45.7 is almost twice of 15 s UD with Weibull modulus of 26.6. Hence, 45 s UD is the most reproducible for both hardness and fluidity tests.

3 Conclusions

(1) Ultrasonically degassing (UD) process is an effective way to enhance the mechanical properties of secondary Al7Si0.3Mg alloy. Both hardness and fluidity of alloy are improved after the UD process. Average efficiency of UD on fluidity measurements is 31.71%, whereas the efficiency on hardness values is 8.48%.

(2) The 45 s UD is the most efficient option with 14.10% increase in hardness, whereas 15 s of UD is the lowest value of 4.8%. The value of 70.08 HB is obtained from UD, which is equivalent to sand casting of primary Al7Si0.3Mg aluminum alloy. The highest value of 56.4 cm for 45 s and the lowest value of 42 cm for 15 s after UD of fluidity were measured.

(3) For fluidity test results, with a 19.5 of Weibull modulus and 45 s UD processing time is the most consistent, reliable and reproducible choice in ultrasonic degassing, and it has almost five times the Weibull modulus with respect to 15 s UD of 4.3 of Weibull Modulus.

(4) For hardness test results, again with a 45.7 of Weibull modulus, 45 s UD processing time is the most consistent and reliable one against 15 s and 30 s UD. It has almost twice the Weibull modulus with respect to 15 s UD of 26.6.

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