Prediction of mechanical properties of Al alloys with change of cooling rate

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Abstract: The solidification process significantly affects the mechanical properties and there are lots of factors that affect the solidification process. Much progress has been made in the research on the effect of solidification on mechanical properties. Among them, the PF (Phase Field) model and CA (Cellular Automata) model are widely used as simulation methods which can predict nucleation and its growth, and the size and morphology of the grains during solidification. Although they can give accurate calculation results, it needs too much computational memory and calculation time. So it is difficult to apply the simulation to the real production process.

In this study, a more practical simulation approach which can predict the mechanical properties of real aluminum alloys is proposed, by identifying through experiment the relationship between cooling rate and SDAS (Secondary Dendrite Arm Spacing) and mechanical properties. The experimentally measured values and the values predicted by simulation have relatively small differences and the mechanical properties of a variety of Al alloys are expected to be predicted before casting through use of the simulation.

Key words: mechanical properties; dendrite structure; aluminum alloy; cooling rate; solidification; casting simulation

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Nowadays, lightweight metals such as aluminum alloys and magnesium alloys are used to reduce the weight of cars, and many other heavy metal products. There has been a lot of research regarding the new alloy development and new casting process development in order to improve the mechanical properties, castability, and casting quality. Meanwhile, a lot of research on the mechanical properties and the behavior of aluminum alloys have been conducted. If the casting conditions or the casting design changes, the existing experimental data is not available; and a new evaluation of the mechanical properties must be made through new experiments. Therefore, further research is needed to accurately predict whether casting defects will occur and how the mechanical properties are changed after casting; and to determine appropriate casting conditions and casting processes for casting products of a variety of sizes and shapes.

Many researchers have conducted a large amount of studies to explain the solidification phenomenon by making physical and mathematical models. Among them, the PF (Phase Field) model and the CA (Cellular Automata) model are widely used as simulation methods which can predict nucleation and its growth, and the size and morphology of the grains during solidification [1]. Although they can give accurate calculation results, it needs too much computational memory and calculation time; so it has been difficult to apply to the real production process. Therefore, in order to save cost and shorten the product development period, it is necessary to study the prediction of the mechanical properties of castings according to how the casting conditions change by building a database through experimental evaluation.

In this study, we are trying to predict the changes in the mechanical properties with the change of cooling rate of the alloy through simulation in order to make prediction of the mechanical properties of the products more practical. In the case of aluminum alloys, the mechanical properties are generally influenced by grain size, inner defects (porosity, inclusion, and micro-shrinkage), SDAS (Secondary Dendrite Arm Spacing), the shape and distribution of primary crystal and eutectic structure, and the cooling rate. Among these factors, SDAS has a great effect on the mechanical properties. The size of SDAS per unit length is influenced by the cooling rate, pouring temperature, impurities in the molten metal, roughness of the mold surface, and mold materials. But it is very difficult to consider all these factors.

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In the present research, casting experiments were conducted with the Al alloys, A4032 and A2. The SDAS was measured by observing the grain structure of the alloy, and the exponents (n) of the empirical equation linking SDAS and cooling rate (CR) were determined.

$$\text{SDAS} = k(\text{CR})^n \quad (1)$$

Finally the mechanical properties (tensile strength, hardness, and elongation) of the cast samples from the casting experiments were measured and curves were fitted to SDAS and cooling rate from the solidification simulation to obtain the final relational expression to provide general data base for the alloy. And then the relationship between mechanical properties and SDAS by curve fitting was determined. By using this procedure, the prediction of the mechanical properties of Al alloys became possible through simulation of the casting process.

2 Experiments and derived correlation equations

2.1 Casting experiments

To find out how the change of mechanical properties depends on cooling rate, a stepped Y-Block permanent mold, as shown in Fig. 1(a), was made. The thinnest part of the casting was 20 mm and the thickest part was 50 mm. A riser was placed on the top of the thickest part for feeding during solidification.

To keep the initial temperature of the mold uniform, the mold was heated in a heat treatment furnace at 200 ℃ for 4 h. After heating, thermo-couples were installed for temperature measurement at the points shown in Fig. 1(b). After that, A4032 or A2 alloy was melted and poured into the mold at 700 ℃ after degassing for 5 min [2]. To obtain the cooling rate, the temperature of the center point of each thickness was stored in the computer every second.

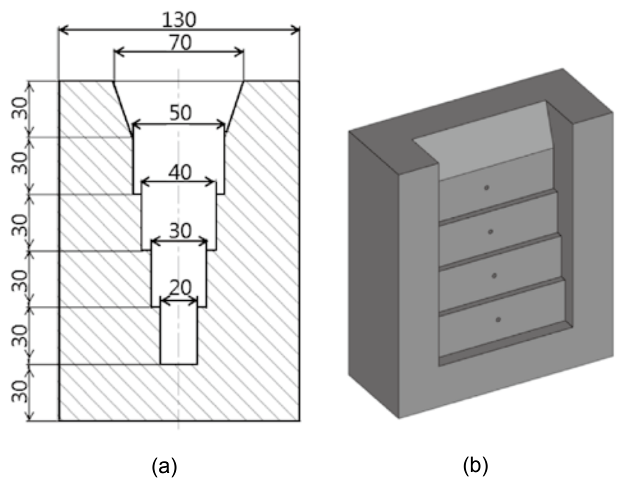


Fig. 1: Dimensions of mold for casting experiments

Figures 2 and 3 are the solidification time-temperature graphs of A4032 and A2 alloy respectively. The graphs show that the difference in the slope of the cooling curves depends on the difference of thickness. From the solidification time-temperature curve, the cooling rate can be calculated by $\Delta T/\Delta t$ (where, ΔT is the temperature difference and Δt is the time difference), but the definitions and methods vary in the literature [3]. In this research, the solidification time (t_f) from the liquidus temperature (T_L) to the solidus temperature (T_S) was used. In other words, the cooling rate of each thickness of the two Al alloys was calculated by using CR = $(T_L - T_S) / t_f$.

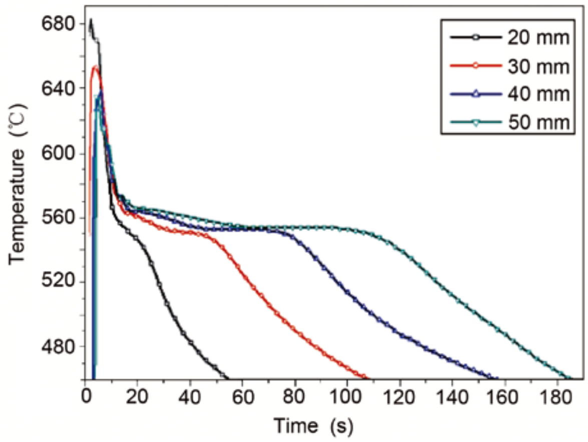


Fig. 2: Cooling curves at different parts of casting for A4032 alloy

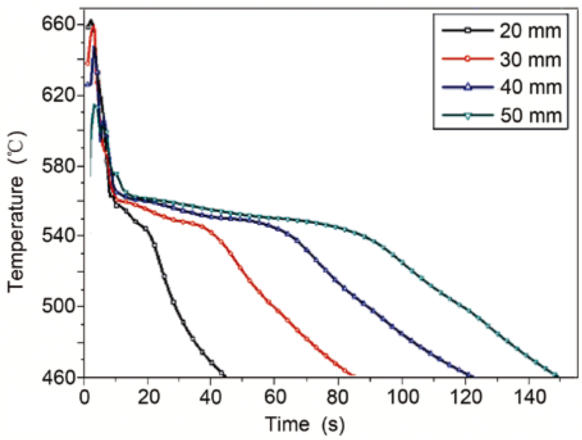


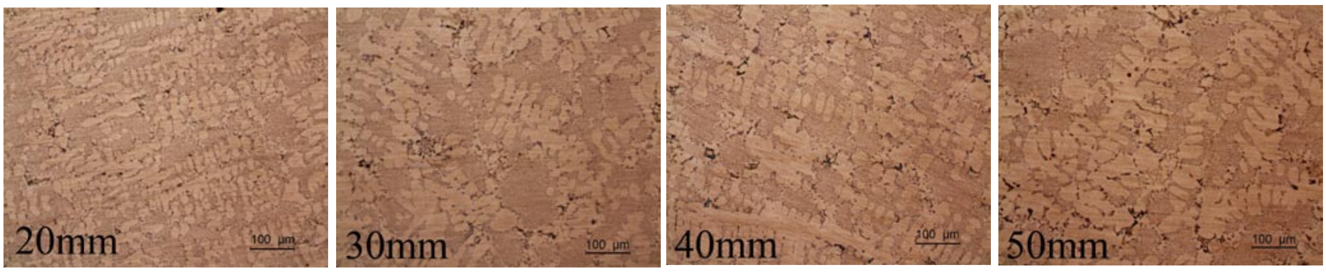
Fig. 3: Cooling curves at different parts of casting for A2 alloy

A specimen of 20 mm × 20 mm × 20 mm size was taken from near the thermocouple and grain structure was observed for measuring SDAS. Figure 4 is the grain structure of the area that is near to the middle of each thickness of the two kinds of Al alloys [4].

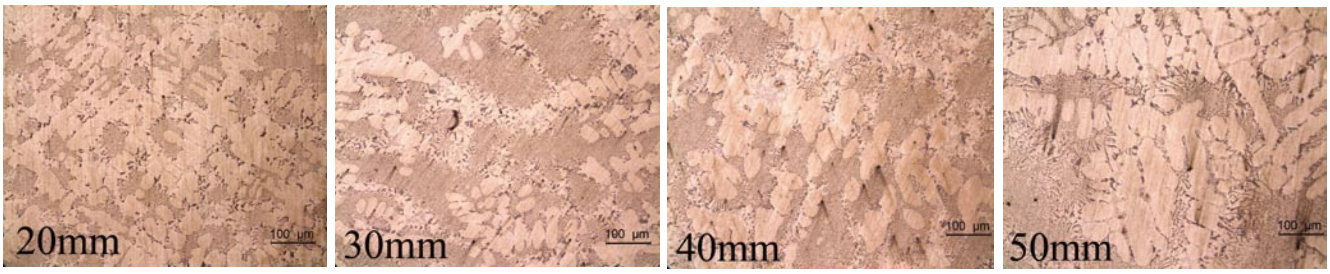
In order to derive the correlation equations between the cooling rate and SDAS, and between mechanical properties and SDAS; the SDAS was first measured by counting the number of grain boundaries in a unit length (100 μm). Then hardness and tensile strength tests on the KS 14A specimen (Fig. 5) made from the casting experiment were conducted.

Tables 1 and 2 show the cooling rate and the SDAS of each thickness of A4032 and A2 alloys.

Tables 3 and 4 show the mechanical properties of each thickness of A4032 and A2 alloys.



(a) A4032 alloy



(b) A2 alloy

Fig. 4: Grain structures of the two alloys

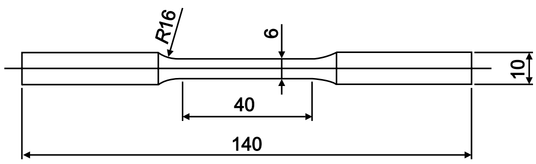


Fig. 5: KS 14A tensile strength test specimen

When we draw graphs using the above data, the relationship between SDAS and cooling rate shows an exponentially decreasing curve; and the relationships between SDAS and the mechanical properties tend to decrease linearly. Therefore, the relationship between SDAS and the cooling rate can be curve fitted using the expression $y = ax^b$ and the relationship between SDAS and mechanical properties can be curve fitted using the expression $y = ax + b$. The coefficients of the correlation equations can be calculated from the fitted curves. Figure 6 shows the relationship between the cooling rate and SDAS; and Figure 7 shows the relationship between the mechanical properties and SDAS.

Table 1: Cooling rate and SDAS of A4032 alloy

Thickness	Cooling rate (˚C·s^{-1})	SDAS (μm)
20 mm	2.43	14.28
30 mm	0.88	18.60
40 mm	0.52	23.52
50 mm	0.35	26.67

Table 2: Cooling rate and SDAS of A2 alloy

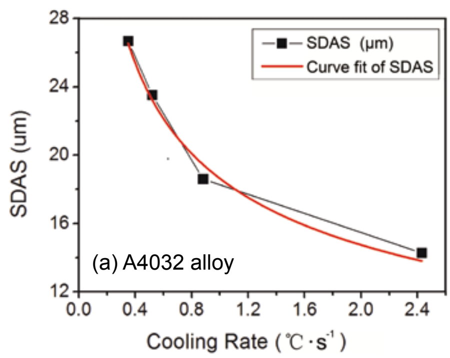
Thickness	Cooling rate (˚C·s^{-1})	SDAS (μm)
20 mm	3.20	28.70
30 mm	1.32	40.00
40 mm	0.83	49.28
50 mm	0.61	55.05

Table 3: Mechanical properties of A4032 alloy

Thickness	TS (MPa)	El (%)	HN (HRF)
20 mm	214	2.3	74.0
30 mm	195	1.6	69.8
40 mm	185	1.5	67.2
50 mm	172	1.3	64.8

Table 4: Mechanical properties of A2 alloy

Thickness	TS (MPa)	El (%)	HN (HRF)
20 mm	261	3.8	73.74
30 mm	245	2.7	70.14
40 mm	233	3.1	67.49
50 mm	217	1.9	65.74



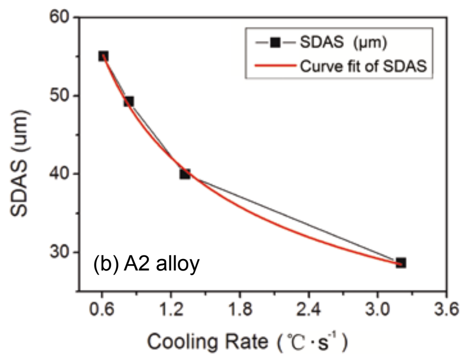
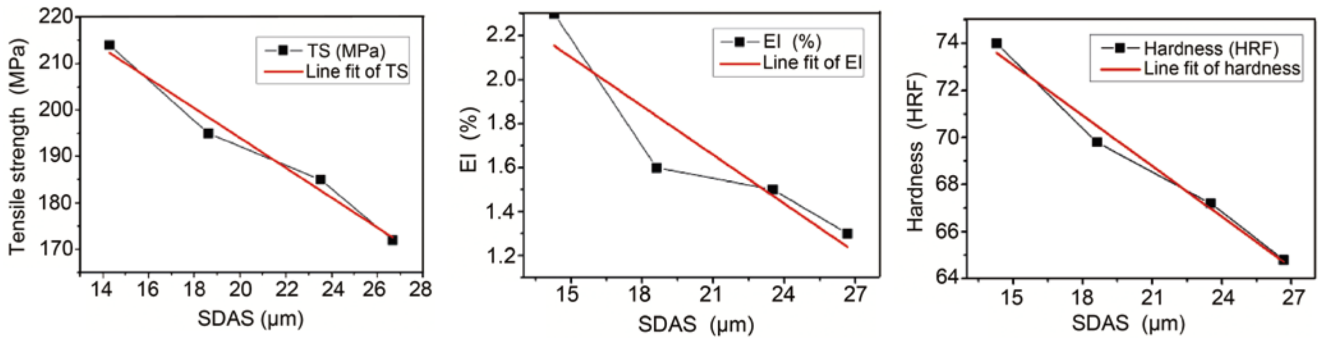
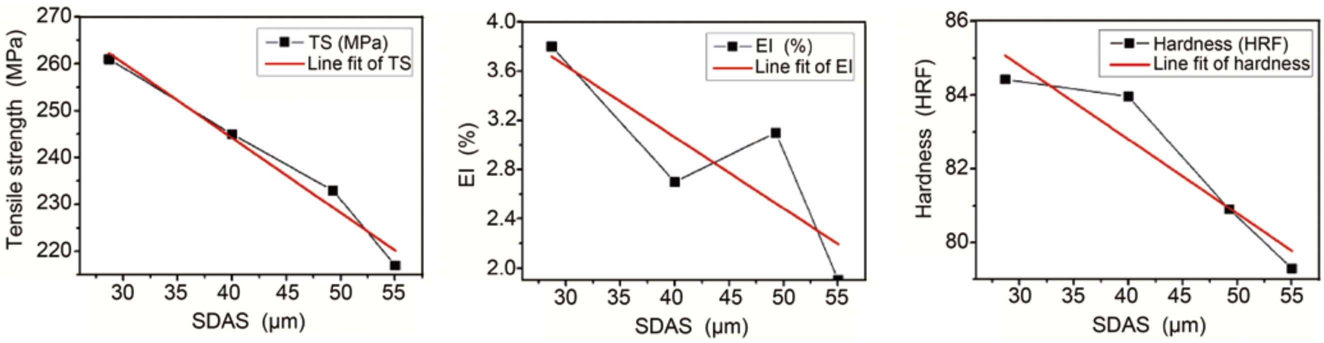


Fig. 6: Relationship graphs between cooling rate and SDAS



(a) A4032 alloy



(b) A2 alloy

Fig. 7: Relationship graphs between mechanical properties and SDAS

After curve fitting, the coefficients of the relationship expressions were obtained and the correlation equations for predicting the mechanical properties of the two Al alloys are shown below.

A4032: SDAS = 18.63 (CR) $^{-0.337}$

TS [MPa] = -3.212 SDAS + 258.21

EL[%] = -0.074 SDAS + 3.21

HN [HRF] = -0.717 SDAS + 83.83

A2: SDAS = 45.3 (CR) $^{-0.398}$

TS [MPa] = -1.596 SDAS + 308.08

EL[%] = -0.058 SDAS + 5.38

HN [HRF] = -0.201 SDAS + 90.85

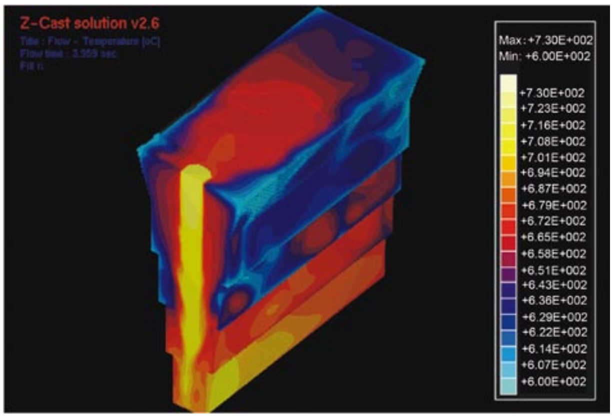


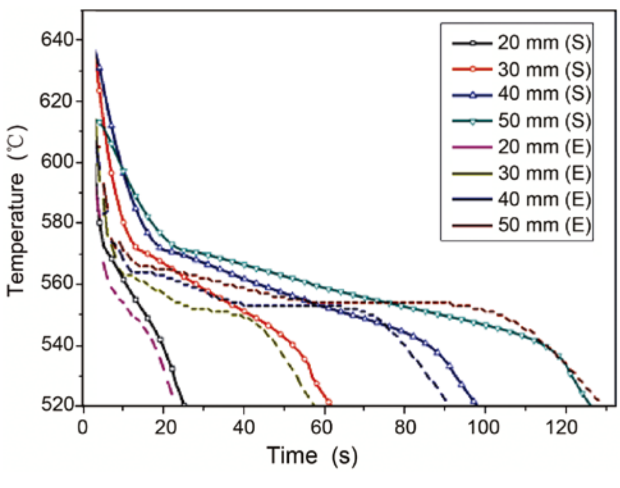
Fig. 8: Temperature distribution after mold filling

3 Simulation and prediction of mechanical properties

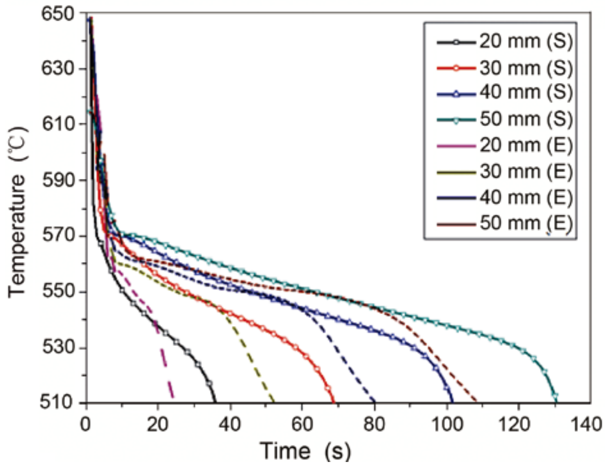
3.1 Flow and solidification simulation

At first, the flow analysis was carried out under the same conditions as with the casting experiment. The pouring velocity was 1.0 m·s^{-1} and pouring time was about 4 s. Solidification analysis was carried out using the temperature distribution after the completion of mold filling [5]. The temperature distribution after mold filling is shown in Fig. 8.

Proceeding with the solidification analysis using the temperature field of mold filling, thermocouples were installed in the same positions as with the casting experiment for storing temperature change during solidification. Figure 9 shows the comparison between the temperature change with



(a) A4032 alloy



(b) A2 alloy

Fig. 9: Comparison of cooling curves produced by experiment and simulation

time of experiment and the simulation at the same position during solidification. The (S) in Fig. 9 means simulation and (E) means experiment.

3.2 Prediction of mechanical properties

The cooling rate can be obtained from the temperature data obtained from the solidification analysis. The mechanical properties can be predicted by substituting the cooling rate obtained from the simulation into the above correlation equations. The mechanical properties obtained are shown in Tables 5 and 6.

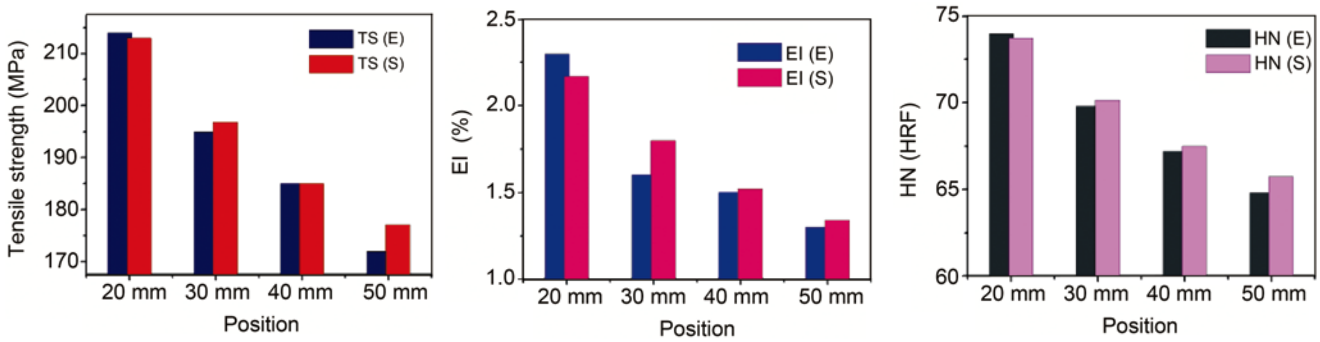
Table 5: Predicted mechanical properties of A4032 alloy

Thickness	TS (MPa)	El (%)	HN (HRF)
20 mm	212.97	2.17	73.74
30 mm	196.84	1.80	70.14
40 mm	184.97	1.52	67.49
50 mm	177.13	1.34	65.74

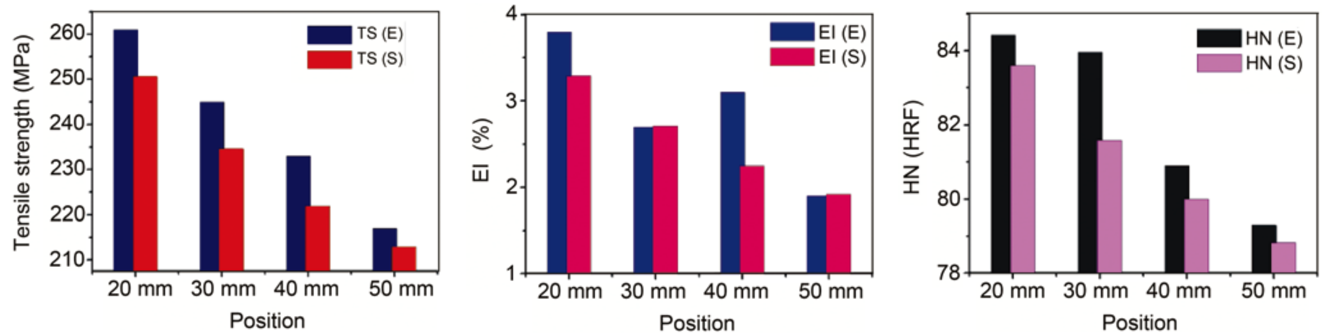
Table 6: Predicted mechanical properties of A2 alloy

Thickness	TS (MPa)	El (%)	HN (HRF)
20 mm	250.59	3.29	83.60
30 mm	234.60	2.71	81.58
40 mm	221.94	2.25	79.99
50 mm	212.81	1.92	78.83

Figure 10 shows bar graphs that compare the mechanical properties measured from the experiment and calculated from the simulation. The smallest difference between experiment and simulation in tensile strength was 0.01% and the maximum difference was 4.98%. The smallest difference in elongation was 0.37% and the maximum difference was 37.77% that may have appeared due to the micro-shrinkages and cavities in the specimen and a temperature difference between experiment and simulation [6, 7]. The smallest difference in hardness was 0.35% and the maximum difference was 2.91%. If we do more experiments for the same material at various cooling conditions, it is expected to be more accurate to predict the mechanical properties by casting simulation. Further research about the effect of the heat treatment on the changes in the mechanical properties is also needed.



(a) A4032 alloy



(b) A2 alloy

Fig. 10: Comparison of mechanical properties produced by simulation and experiment

4 Conclusions

Stepped mold casting experiment and simulation about Al A4032 and A2 alloys were carried out. The following conclusions were obtained.

(1) The relationships between the cooling rate and SDAS and between the mechanical properties and SDAS are obtained from changes in the cooling rate, grain structure, and mechanical properties occurring due to the difference in thickness of casting during solidification.

(2) The bar graphs comparison shows the mechanical properties measured from the experiment and calculated from the simulation with an difference of 0.01% to 4.98% in the tensile strength, 0.37% to 37.77% in the elongation and 0.35% to 2.91% in the hardness.

(3) It will be possible to predict the mechanical properties through simulation before real casting by building correlation equations to forecast the mechanical properties with the cooling rate through experiment on a variety of casting alloys in the same way as in the present study.

References

[1] Kwon H J. Prediction of Mechanical Properties and Microstructure of Hypo-eutectic Al-Si Alloy using Cellular Automata; Based on experimental database. Master’s thesis, Yonsei University, Korea, 2003. (in Korean)

[2] Lee W S and Ye B J. Variation of Fluidity in Al Alloys with the Addition of Si, Mg and Melt Treatments. Journal of the Korea Foundry Society, 1999, 19(4): 310–317. (in Korean).

[3] Cheon B W. The Effect of Metallic Mold Cooling System on the Solidification Structures and the Mechanical Properties for Al Alloy Castings. Master’s thesis, Dong-A University, Korea, 1995. (in Korean)

[4] Kim J K, Kim KY, and Park H W. Metallurgical microscope histology. Gold Publishing House, Korea, 1999: 369–387.(in Korean).

[5] Yoo S M, Lee D H, Kim J K, et al. Three Dimensional Solidification Analysis in Large Steel Castings by Modified Finite Difference Method. Journal of the Korea Foundry Society, 1991, 11(1): 54–62. (in Korean)

[6] Lee M S, Kim K Y, and Kim S W. Effect of Tilting Speed and Angle on Gas Entrapment in Gravity Diecasting. Journal of the Korea Foundry Society, 1994, 14(4): 353–362. (in Korean)

[7] Han Y S. Defect Types of High Pressure Casting and the Influence on the Mechanical Properties. Journal of the Korea Foundry Society, 2002, 22(5): 223–230. (in Korean)

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