Influence of Ageing Behavior on Hardness of Squeeze Cast Al 7075 - 2.5% TiCp Using Response Surface Methodology

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Abstract

In this work, the effect of precipitation hardening on hardness of Al 7075 reinforced with 2.5 % TiC_p has been investigated. The composite is fabricated by employing squeeze cast process, in which the combination of both casting and forging processes can be done under high pressure. Squeeze casting is chosen for this work since this process results in negligible porosity, refined grain structure and high quality cast composites. The precipitation hardening process is carried out within a temperature range of 130 – 210 °C for the time interval of 1-8 hours. Hardness is recorded to closely monitor the age hardening effect and is employed to ascertain the optimum hardness using SYSTAT as a tool.

***Key words**: Precipitation hardening, squeeze casting, TiC_p, Response Surface Methodology [RSM], Aluminum metal matrix composite [Al MMC]*

1. INTRODUCTION

In the current industrial scenario, metal matrix composite materials fabricated with micro particles are gaining currency in defense, aerospace, automobile industries and electronic packaging applications due to their high strength to weight ratio, good machinability etc. In particular, Al metal matrix composites have wider applications due to their drastic weight reduction and exceptional properties like high wear and corrosion resistance, metallurgical and tribological properties, which require high creep resistance, good thermal conductivity, low thermal expansion co-efficient which is achieved by new fabrication techniques and methods.

Here, TiC_p reinforcements are used to fabricate Al 7075 composites by squeeze casting process under high pressure. Then the cast samples are subjected to precipitation hardening treatment mainly to improve the hardness of the samples.

Dineshkumar[1], et al. found that metal matrix composites can lead to significant savings in materials and energy and reduce pollution through the application of ultra-strong material properties. Sathishkumar[2], et al. observed that the age hardening response of the composites is faster than the alloy due to the presence of particulate reinforcements that can accelerate the aging kinetics. Micro structural examination of the composites reveals uniform distribution of reinforcement in the matrix. The squeeze cast pressure, die pre-heating temperature and compression holding time are the parameters making the significant improvement in the mechanical properties of Al MMCs.[3, 4] The age hardening and annealing heat treatment operations can eliminate the micro-segregations and improve the mechanical properties of Al 7075 alloy and this can be achieved by rapid solidification and appropriate heat treatment process [5].

The hardness of the as cast sample shows an increased hardness due to heat treatment[6]. The aged material is generally stronger than the as-cast material and an appropriate solution treatment temperature and holding time have decisive effects on the strengthening, hardening and ductility of the alloy[7]. The mechanical properties of the composite are higher in age hardened samples than the as cast samples, most likely due to the precipitation of a second phase during ageing which covers the *surface at the particles-matrix interfaces. The hardness increases with aging time[8]. The use of micro particles gives better results in ultimate tensile strength and hardness[9]. Hardness, density increases with increases in TiC and TiO_2 content in Al composite material [10].*

The wear rate decreases linearly with increases in volume fraction of titanium carbide. Average co-efficient of friction also decreases linearly with increasing normal load and volume fraction of TiC_p[11]. Rai[12] et al. revealed that microstructure of the composites showed uniform distributions of TiC_p particles along the grain boundaries. The presence of TiC_p particles in the composite increased the yield strength and hardness with substantial decrease in elongation. Azeemdafedar[13], et al. found that TiC_p in metal matrix composite is used in aerospace industry. Mitraakhtari Zarareh[14], et al. presented that the variation in the composition of the material can yield significant differences in microstructure. In addition to the eutectic microstructure, spherical TiC_p grains coexisting with a eutectic mixture are possible at high TiC_p content. Adding hard TiC_p increases cutting speed, fewer particles are broken, resulting in reduced tool abrasion wear which improves tool life[15].

2. MATERIALS SELECTION

The qualitative chemical analysis is performed using spectroscopic analysis and the chemical composition of Al 7075 is given in Table 1 and its properties are shown in Table 2.

Table 1 Chemical composition of Al 7075

Element	Si	Fe	Mn	Mg	Cu	Zn	Ti	Cr	Al
Al 7075	0.4	0.5	0.30	2.9	2	6.1	0.2	0.28	Bal

Table 2 Properties of Al 7075 & Reinforcements

Element	Density, g/cm^3	Melting point, °C	Modulus of elasticity, Gpa	Thermal conductivity, W/m.k
Al 7075	2.8	635	71.7	130
TiC_p	4.93	3250	450	28.9

Since TiC_p has a wide range of commercial applications such as jet propulsion systems, abrasive materials, cutting tools, grinding wheels and coated cutting tips and excellent properties, TiC_p is used as reinforcement material in this research work.

3. EXPERIMENTAL WORK

In this study, Al 7075 has been used as base matrix material. TiC_p powder with 99% purity of metal base of average particle size of 2 micron is imported from M/s. Alfa Aesar, USA used as reinforcement material. 2.5% of TiC_p are preheated in the muffle furnace at 500 ºC for 2 hrs to improve the wettability, bonding between the matrix and the reinforcement material. Molten metal is prepared using electrical resistance crucible furnace as shown in Figure 1 and the squeeze cast operating parameters are given in Table 3. The pre-heated reinforcement material is poured into the furnace and finally the squeeze cast of 50 mm diameter and 220 mm length is obtained. 40 samples for heat treatment process are cut using wire EDM machine with 50 mm diameter and 10 mm height.

Table 3 Squeeze casting operating parameters

Furnace temp, °C	Melt temp, °C	Stirrer speed, rpm	Stirrer holding time, min	Squeeze pressure, bar	Squeeze holding time, min
800	736	600	30	35	10

Figure1. Squeeze Casting set up

Figure 2. Muffle furnace

4. PRECIPITATION HARDENING HEAT TREATMENT

After cleaning the as cast samples, precipitation hardening or age hardening tests are carried out in the muffle furnace which is shown in figure 2. With the ageing temperature range of 130-210ºC and the ageing time of 1-8 hours, then followed by atmospheric cooling to room temperature. Micro hardness values are recorded using Wilson hardness Vickers 402 MVD Tester at 300 kgf load with a dwell time of 10 seconds. All 40 samples are used for hardness testing in accordance with ASTM standard E18-02. As casted Al 7075 composite have resulted in lower hardness 110 VHN is noticed.

5. MATHEMATICAL MODELING USING RSM

5.1 Response Surface Methodology

The experimental trials are conducted using SYSTAT by applying Box Behnken design technique. It is a factorial design for three factors and 15 runs with design of experiment method. Hardness as response, whereas temperature, time and solutioning hour are independent variables used as process parameters as shown in Table 4. To predict the response variable hardness, using the ageing temperature, ageing time, solutioning hour, and a novel mathematical model is developed by using the equation (1) through RSM topologies.

$$H = f(C, T, S) \qquad (1)$$

General equation for polynomial regression co-efficient is used to predict the hardness value is given below.

$$H=\alpha_0+\alpha_1 C+\alpha_2 T+\alpha_3 S+\alpha_{11} C^2+\alpha_{22} T^2+\alpha_{33} S^2+\alpha_{12} CT+\alpha_{23} TS+\alpha_{31} SC \qquad (2)$$

The mathematical model was developed by RSM to determine the hardness related to corresponding parameters is given below.

$$H = -207.564 + 3.129 \times C + 33.658 \times T + 28.762 \times S - 0.008 \times C^2 - 0.442 \times T^2 - 7.191 \times S^2 - 162 \times CT \quad (3)$$

Table 4 Process parameters

S.No.	Parameters	-1	0	1
1	Temperature C, ° C	150	190	210
2	Time T, Hr	1	5	7
3	Solutioning hour S, Hr	1	2	3

Table 5 Design matrix and its results

Run	Coded values			Actual values			Experimental Hardness (H),VHN	Predicted hardness using RSM	% Error
	C	T	S	Temp °C	Time T, Hr	Solutioning hour, S, Hr			
1	-1	-1	0	150	1	2	115.13	119.46	-0.037
2	1	-1	0	210	1	2	120.16	124.68	-0.037
3	-1	1	0	150	7	2	157.83	157.12	-0.234
4	1	1	0	210	7	2	89.16	94.30	-0.057
5	-1	0	-1	150	5	1	131.26	139.09	-0.059
6	1	0	-1	210	5	1	85.53	105.43	-0.232
7	-1	0	1	150	5	3	131.26	139.03	-0.059
8	1	0	1	210	5	3	100.53	105.43	-0.048
9	0	-1	-1	190	1	1	122.26	132.96	-0.087
10	0	1	-1	190	7	1	114.17	118.2	-0.035
11	0	-1	1	190	1	3	118.26	122.14	-0.032
12	0	1	1	190	7	3	112.45	118.2	-0.051
13	0	0	0	190	5	2	134.2	130.24	0.029
14	0	0	0	190	5	2	134.2	130.24	0.029
15	0	0	0	190	5	2	134.2	130.24	0.029

Table 6 Analysis of Variance

Source	df	Type I SS	Mean Squares	F-Ratio	p-Value
Regression	9	4,741.793	526.866	9.995	0.010
Linear	3	3,135.525	1,045.175	19.827	0.003
Quadratic	3	376.895	125.632	2.383	0.186
Interaction	3	1,229.373	409.791	7.774	0.025
Residual Error	5	263.567	52.713		
Total Error	14	5,005.360			

Table 6 shows the error value for the parameters temperature, time, and solutioning hour. These results are recorded from least square values obtained from ANOVA. In order to validate the regression model, trial run hardness values are plotted in Figure 3 and it shows that the experimental values are closer to the theoretical values, which indicates the model is adequate.

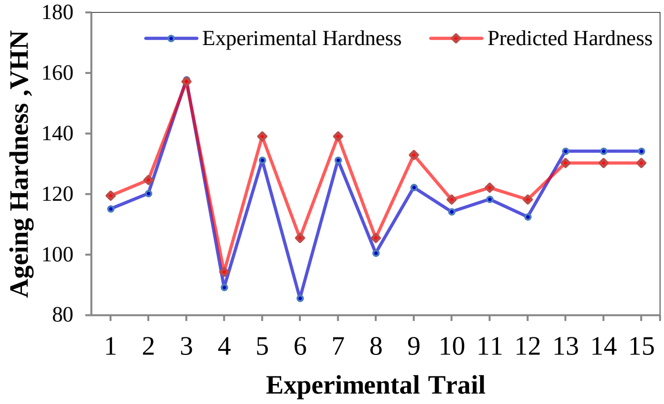

Figure 3 Graph showing Experimental hardness vs Theoritical hardness

6. RESULTS AND DISCUSSION

It is evident that at higher temperatures, the movement of solute is faster and ageing takes place faster at higher temperature but equilibrium and stability at high temperatures of solute is affected and hence, it may lead to lower hardness[8]. The ageing hardness recorded for each temperature from 130 – 210ºC for different ageing time intervals 1- 8 hours have been attempted and developed model through RSM.

6.1 Sensitivity Analysis

Sensitivity analysis is a method to identify parameters and rank by order to calculate the output. Mathematically, sensitivity of a design objective function with respect to a design variable is the partial derivative of that function with respect to its variables. To obtain the sensitivity equation for hardness, eqn. (3) is differentiated with respect to hardness. The sensitivity equation (4), (5) and (6) represent the sensitivity of hardness for temperature (C), Time (T), and solutioning hour (S) respectively.

$$\delta H/\delta C = 3.129 - 0.016 \times C - 0.162 \times T \quad (4)$$

$$\delta H/\delta T = 33.658 - 0.884 \times T - 0.162 \times C \quad (5)$$

$$\delta H/\delta S = 28.762 - 14.382 \times S \quad (6)$$

Figure 4 indicates that ageing temperature is the predominant and most sensitive parameter in increasing the hardness when compare to other two parameters and Figure 5 shows that age hardening time is the second influencing parameter than solutioning time as it is more negative. Figure 6 indicates solutioning hour having less impact than ageing temperature and ageing time. Figure 7 shows the interaction effect of temperature , time on hardness which says that time increases hardness is also increases. peak hardness is recorded on 150°C,7 hrs is 150 VHN.

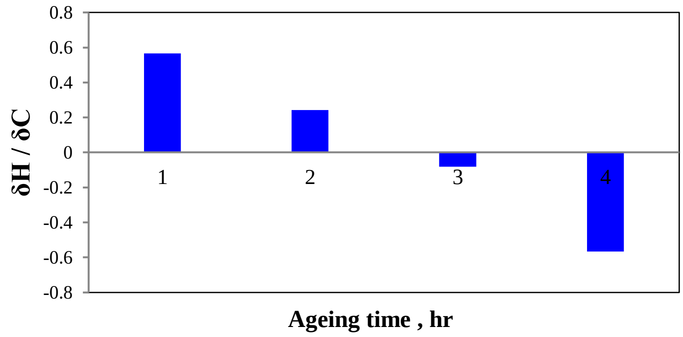

Figure 4 Sensitivity graph for Temperature

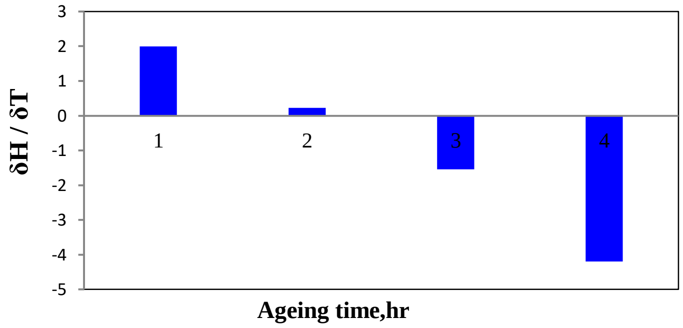

Figure 5 Sensitivity graph for Time

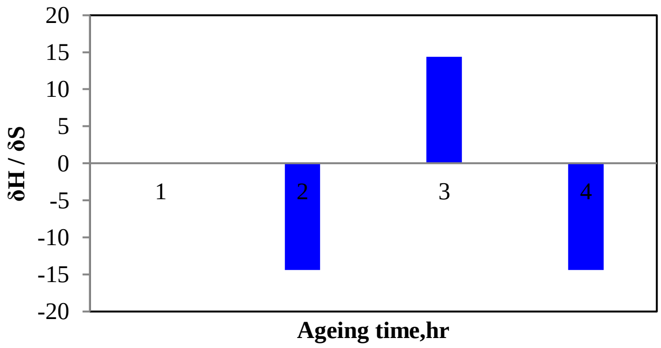

Figure 6 Sensitivity graph for Solutioning hour

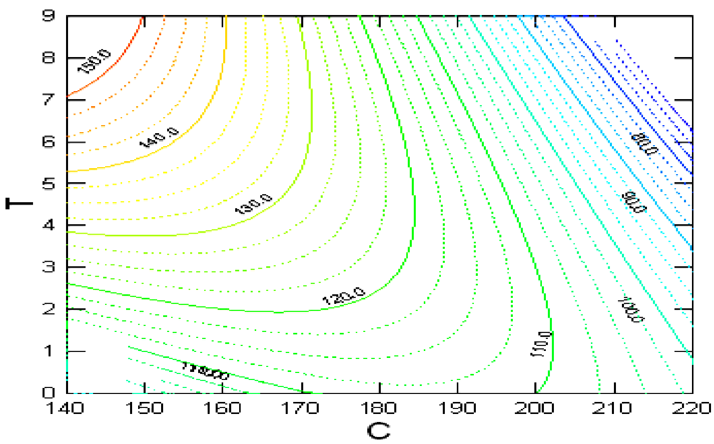

Figure 7 Contour plot for the prediction of Temp,Time and hardness

CONCLUSION

By conducting the heat treatment and hardness tests on Al 7075 reinforced with 2.5% TiC is fabricated by squeeze casting technique under process controlled parameters, the following conclusion are drawn.

- As cast Al 7075 composites has resulted in lower hardness 110 VHN is noticed.
- Precipitation hardened Al alloy has better hardness value of 157.83 VHN compared to as cast composite alloy.
- Mathematical modeling is done using SYSTAT and it is found that the theoretical and experimental hardness values are within the close tolerance limit and also the percentage of error is found to be minimum and that the predicted model is adequate.
- Addition of TiC_p has improved the hardness. The highest hardness of 157.83 VHN for Al 7075 alloy is experimentally obtained at the ageing temperature of 150ºC for an ageing period of 7 hours and solutioning time of 2 hrs.
- Temperature is the dominant sensitive parameter when compared to time and solutioning hour.
- RSM results shows that having a good agreement with the experimental results. Hence the developed model is adequate.

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