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Optimization of Fluidity and Mechanical Properties of the Sand Casting A518 Alloy by Using Grey Relational Analysis Method

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Abstract. Thin-wall castings are carried out on A518 alloy, which is known for poor cast-ability which results in fluidity, which in turn may affect the quality of the castings. In the present investigation, the effect of green sand casting process parameters viz. Scrap, Al-2.5Ti-0.25C, SiC, and pouring temperature on the enhancement of fluidity and mechanical properties of the A518 alloy were optimized by Taguchi-based grey relational analysis (GRA). It was observed that optimized parameters obtained from GRA produced a casting with improved properties. Analysis of variance shows the pouring temperature has a significant influence by 30.02%, while Al-2.5Ti-0.25C has an effect of 18.41%, and SiC at 8.92% on the performance characteristics i.e. fluidity and mechanical properties. Confirmation experiments were performed at the optimal parametric combination. The metallurgical characterizations of optimized casting A518 alloy were also studied using Microstructure analysis.

Keywords: Sand casting; A518 alloy; fluidity; scrap; mechanical properties; grey relational analysis.

INTRODUCTION

Metal casting, one of the primary manufacturing processes, is known to human beings for several centuries. It is a versatile process capable of being used in the production of castings ranging from very large shapes to small intricate ones. The structures and sub-assemblies of several machines and machine tools are made by casting [1-2]. The industrial demand of thin-wall castings in aluminium alloys is of significant role in order to produce high strength to weight ratio components. The production of thin-wall castings is limited by the fluidity of the molten metal [4-5]. Fluidity, in the foundry science, is defined as the ability of molten metal to flow before stopped by solidification. It is quantified by measuring the length [6]. The pouring temperature has a great impact on the fluidity and it is an important parameter in measuring the fluidity. Few researchers carried out experimentation on influence of pouring temperature and grain refinement on fluidity [7-11] and found that the effect of pouring temperature and grain refinement on fluidity depends upon several factors such as alloy composition, mode of solidification, type and amount of grain refiner, etc. Sabatino and Arnberg [12] studied that major additions of magnesium and copper on series of 500 and 200 alloys caused in longer freezing ranges, which in turn might lead to hot tearing. Birru et al. [13] observed that the fluidity was increased by the addition of scrap especially at higher pouring temperature and coated spirals for Aluminium-Zinc alloys.

This means that GRA technique is simple and effective tool to solve the multiple objective problems. GRA is a technique of multi-objective optimization which solves by converting the multi-objective function into a single objective function. Hence, authors made an attempt to obtain optimal settings of significant process parameters and their influence on the fluidity and mechanical properties of sand-cast A518 alloy by using GRA method.

MATERIALS AND METHODOLOGY

Materials used for fluidity testing

The standard chemical composition of the A206 alloy is shown in Table 1. The A518 master alloy was made by sand casting in an ingot form with ordinary crucible melting furnace. It was made with 5 kg 99.9% pure aluminium (Al) was melted in a graphite crucible at a temperature of 750 °C, in which 4.5 wt. % copper (99.8% purity) was introduced in a rod form to the molten aluminium at 800°C. Later, the grain refiner Al-2.5Ti-0.5C was prepared with 2.5 wt. % of titanium metal powder (99.8% purity) mixed with 0.5 wt. % carbon powder (150 microns size) for 1kg aluminium. The fluidity was tested by the addition of the aluminium scrap (5-15 wt. %) in the form of turning chips to the A518 alloy and it was ensured that its composition would be same as the virgin A518 alloy. Also, Al-Sic master alloy was prepared with the Silicon (Si) metal which was processed into chips by drilling machine for 0.5 kg aluminium. Both scrap and Al-Sic were added into A518 alloy molten metal along with grain refiner at different percentages in order to study their effect on fluidity and mechanical properties.

TABLE 1. A518 Alloy Composition

Alloys	Proportion of the constituting elements (% by weight)						
	Silicon	Copper	Manganese	Magnesium	Zinc	Others	Aluminum
A518	--	--	--	8.0	--	>0.5	Balance

The castings for testing fluidity and mechanical properties were made with the green sand moulds. The green sand was made from silica sand bonded with bentonite clay; molasses, fly ash and water were added in proportionate quantities in order to enhance the properties of green sand. A soapstone powder mould coating was applied to mould surface because the contact angles are large, and the wettability between the molten metal and mould is very low; which in turn caused to enhance fluidity in the thin section.

The effect of thin cross-section on the fluidity and mechanical properties of the A518 alloy is the motive behind the present investigation. Mansour Borouni et al. [11] have selected a cross type gated pattern with various cross-sections for the fluidity test. The similar type of fluidity test pattern has been selected for the present investigation as shown in Fig. 1.

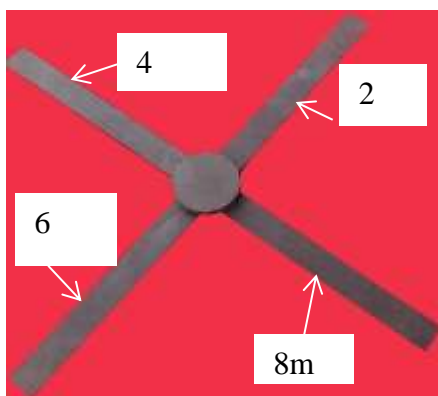


FIGURE 1. Fluidity pattern for the present investigation

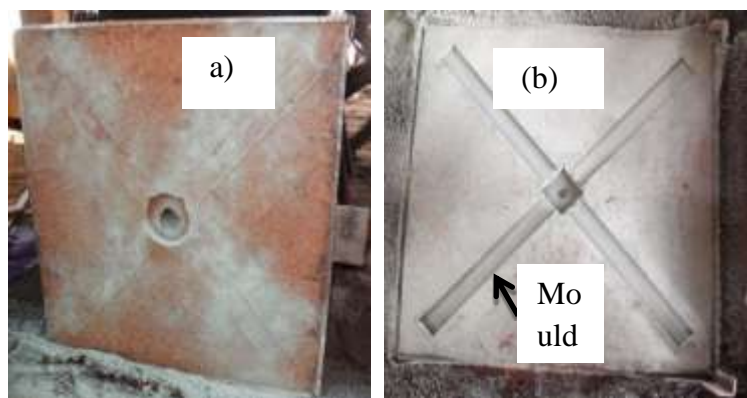


FIGURE 2. Green sand moulds for investigation of fluidity (a) Cope (b) Drag

TABLE 2. Process parameters of A518 alloy

Level	Process Parameters			
	Scrap (Wt. %)	Al-2.5 Ti-0.5C (Wt. %)	SiC (Wt. %)	Pouring Temperature (°C)
1	1.5	0.00	0.00	700
2	2.0	0.15	0.04	750
3	----	0.25	0.07	800

The pattern was made with the mild steel and its design consists of four straight thin channels of 250 mm long and 30 mm width with rectangular cross-sections of 2 mm, 4 mm, 6 mm, and 8 mm thickness. Fig. 2 (a) shows the cope consists of pouring cup and down sprue. Fig. 2(b) depicts the drag half of the pattern consists of the designed pattern. The prepared green sand moulds which are coated with soapstone powder of a designed pattern for all the eighteen fluidity tests.

Methodology

Design of experiments

The fluidity increases in green sand moulds due to less heat transfer rate as compared to core sand moulds [15]. The cause and effect diagram of the sand casting process for A518 alloy comprises of all the above-said process parameters as shown Fig. 3. The selected process parameters of the green sand casting of A518 alloy and their levels are given in Table 2. Generally, the total degrees of freedom for an L₁₈ OA must be more than or equal to that of the process parameters. Thus, the degree of freedom equal to 17 was chosen for the present investigation.

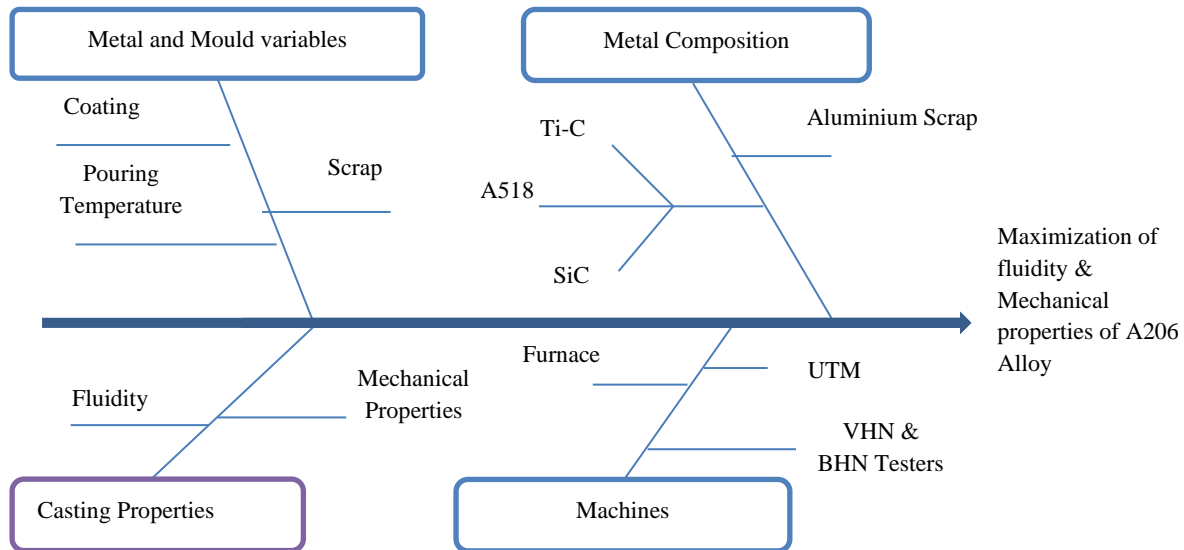


FIGURE 3. Cause and effect diagram.

The experiments were carried out as per the design of experiments and measured the fluidity as given in Table 3.

TABLE 3. L₁₈ Design matrix and Experimental results of A518 alloy

Exp. No.	A	B	C	D	Fluidity length ^a (cm)	Mechanical properties		
						Tensile strength ^a (MPa)	VHN ^a	BHN ^a
1	1	1	1	1	61.50	75.345	83.95	72.9
2	1	1	2	2	65.00	65.219	66.9	51.1
3	1	1	3	3	70.20	132.931	90	81
4	1	2	1	1	59.50	125.601	83.78	67
5	1	2	2	2	80.00	120.27	85.4	58.2
6	1	2	3	3	103.20	82.97	672.68	60.66
7	1	3	1	2	75.20	101.316	75.67	70.3
8	1	3	2	3	80.20	100.695	73.9	63
9	1	3	3	1	91.70	113.816	76.6	66
10	2	1	1	3	89.70	103.556	79	68.12
11	2	1	2	1	87.14	100.7	81.1	70.5
12	2	1	3	2	84.00	93.6	69.67	65
13	2	2	1	2	89.20	108.3	78.58	64.34
14	2	2	2	3	82.10	95.141	73.8	62.5
15	2	2	3	1	68.50	115.11	84.2	64.69
16	2	3	1	3	85.69	123.46	60.5	73.39
17	2	3	2	1	85.00	100.01	65.4	50.3
18	2	3	3	2	73.00	63.843	67.56	61.21

^a Average of three experiment results

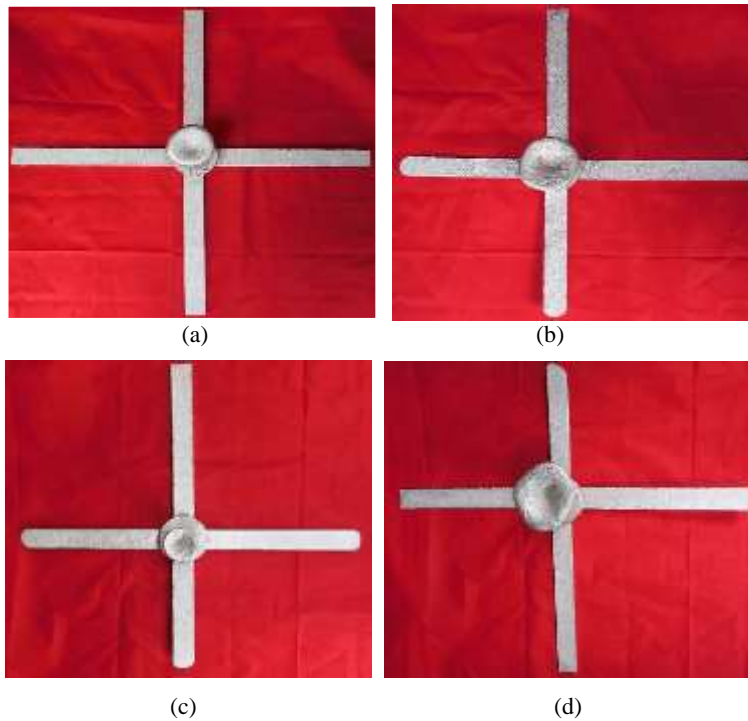


FIGURE 4. Fluidity castings for maximum: (a) Fluidity (b) Tensile strength, (c) VHN and (d) BHN.

Fig. 4 shows the fluidity castings obtained at certain experimental conditions. The mechanical properties such as tensile strength, BHN, VHN values are measured for all 18 castings. The fluidity increased with the increase of cross-section. Hence, samples prepared from 8 mm cross-section channel for maximum fluidity and mechanical properties have taken for characterization and microstructure analysis. The maximum fluidity obtained in sixth number casting obtained mainly at the pouring temperature 700 °C and grain refiner 2.5 wt.% as shown in Fig 4 (b). Similarly, the castings for maximum tensile strength and hardness values (VHN & BHN) obtained at their respective conditions mentioned in Table 3 as shown in Fig. 4 (c) and Fig. 4 (d).

Tensile test

To evaluate the tensile test, eighteen (18) tensile specimens were prepared according to ASTM: B557 standards as shown in Fig.5. Further, all rectangular samples subjected to tensile testing by universal testing machine.



FIGURE 5. Tensile specimens made for the current investigation.

VHN and BHN tests

Vickers hardness tester was used to measure the microhardness value in terms of Vickers hardness number (VHN) of all 18 specimens prepared from 8 mm cross-section thickness according to the standards of ASTM E- 384. And, Brinell hardness tester was used to measure macro hardness in terms of Brinell hardness number (BHN) of the all the above said eighteen specimens according to the standards of IS 1500-2005 respectively A diamond indenter was used to make the indentation spot on the top surface of the specimen which can be measured and transformed into the value of hardness. The VHN test was conducted at a load of 500 gram-force and time of dwelling has been taken as 10 seconds, whereas the BHN test was conducted at a load of 250 kg. The average of three random values of hardness was measured, which are mentioned in Table 3.

RESULTS AND DISCUSSIONS

Data pre-processing or Normalization of experimental results

In GRA, Data pre-processing is very much essential required especially when there is too much scattering in sequence range. It is a process by which shifting the original sequence to an equivalent sequence. The significant objective of the current investigation was to enhance the fluidity and mechanical properties i.e., performance characteristics of the A518 alloy. Therefore, the “larger-the-better” characteristic has been chosen for experimental data pre-processing, which can be done as follows:

$$X_i^*(k) = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)} \quad (1)$$

Where, $X_i^*(k)$ and $x_i(k)$ are the data after normalization and the experimental data respectively for i^{th} number of experiment and k^{th} the response. The normalization of experimental results are as represented in Table 4.

4.2 Effect of GRG on multi-performance characteristics of the A206 alloy

Now, $\Delta_{oi}(k)$ is the deviation sequence value of $X_0^*(k)$ and $X_i^*(k)$, that is

$$\Delta_{oi}(k) = |X_0^*(k) - X_i^*(k)| \quad (2)$$

Grey relational coefficient can be measured with the deviation sequence and expresses the relationship between the ideal and actual normalized experimental results, which can be determined by the following formula:

$$\xi_i(k) = \frac{\Delta_{min} + \zeta \Delta_{max}}{\Delta_{oi}(k) + \zeta \Delta_{max}} \quad (3)$$

Where, ζ is distinguishing coefficient, is considered as 0.5 for all the parameters of equal preference. Next, the Grey relational grade (γ) is calculated by the mean value of the grey relational coefficient of each response.

$$\gamma_i = \frac{1}{n} \sum_{k=1}^n \xi_i(k) \quad (4)$$

TABLE 4. Normalization of the experimental results

Expt. No.	Fluidity length	Tensile strength	VHN	BHN
1	0.046	0.166	0.038	0.044
2	0.126	0.020	0.010	0.009
3	0.245	1.000	0.048	0.057
4	0.000	1.000	0.038	0.035
5	0.469	0.946	0.041	0.021
6	1.000	0.321	1.000	0.024
7	0.359	0.629	0.025	0.040
8	0.474	0.618	0.371	0.028
9	0.737	0.838	0.026	0.033
10	0.691	0.666	0.512	0.036
11	0.632	0.618	0.034	0.040
12	0.561	0.499	0.254	0.031
13	0.680	0.746	0.030	0.030
14	0.517	0.525	0.368	0.027
15	0.206	0.860	0.039	0.031
16	0.599	1.000	0.000	0.045
17	0.584	0.523	0.008	0.008
18	0.309	0.000	0.196	0.025

Where, γ_i is the GRG for the i^{th} experiment number and n is the response characteristic number

The grey relational coefficients and GRG values are depicted in Table 5.

Where, ζ is distinguishing coefficient, is considered as 0.5 for all the parameters of equal preference. Next, the Grey relational grade (γ) is calculated by the mean value of the grey relational coefficient of each response.

$$\gamma_i = \frac{1}{n} \sum_{k=1}^n \xi_i(k) \quad (5)$$

Where, γ_i is the GRG for the i^{th} experiment number and n is the response characteristic number

The grey relational coefficients and GRG values are depicted in Table 5.

TABLE 5. Grey relational and Grey relational grade of the experimental results

Expt. No.	Grey relational coefficients				GRG	Rank
	Fluidity length	Tensile strength	VHN	BHN		
1	0.344	0.375	0.342	0.343	0.354	8
2	0.364	0.338	0.336	0.335	0.346	11
3	0.398	1.000	0.344	0.346	0.581	1
4	0.333	1.000	0.342	0.341	0.558	7
5	0.485	0.903	0.343	0.338	0.577	4
6	1.000	0.424	1.000	0.339	0.808	12
7	0.438	0.574	0.339	0.342	0.450	3
8	0.487	0.567	0.443	0.340	0.499	14
9	0.655	0.756	0.339	0.341	0.583	13
10	0.618	0.600	0.506	0.342	0.575	9
11	0.576	0.567	0.341	0.343	0.495	2
12	0.532	0.500	0.401	0.340	0.478	16
13	0.609	0.663	0.340	0.340	0.537	10
14	0.509	0.513	0.442	0.340	0.488	15
15	0.386	0.781	0.342	0.340	0.503	5
16	0.555	1.000	0.333	0.344	0.629	6
17	0.546	0.512	0.335	0.335	0.464	18
18	0.420	0.333	0.383	0.339	0.379	17

In essence, the larger the GRG represents the product quality nearer to the ideal value and it is desired for optimum quality in castings [14-15]. The complete assessment of fluidity and mechanical properties is based on the GRG. It was observed that the third number experiment i.e. Scrap (Wt. %)-1.5, Al-2.5Ti-0.5C (Wt. %)- 0.15%, SiC (Wt.%)- 0.07%, Pouring Temperature- - 800 °C has the best multi-performance characteristics among eighteen experiments because it has the highest GRG value 0.808. The process parameter optimum level was the level at which highest GRG is obtained. The main effect i.e. difference between the maximum and the minimum values, which describe the significance of process parameters on the multi-performance characteristics as shown in Table 6. The maximum main effect value from the results indicated that the pouring temperature is the most influential parameter among the other process parameters.

Table 6 Mean Responses for overall grey relational grade

Designation	GRG			Main effect (Max-Min)	Rank
	Level 1	Level 2	Level 3		
A	*0.5285	0.5054		0.0231	4
B	0.4713	*0.5787	0.5009	0.1074	2
C	0.5173	0.4781	*0.5553	0.0772	3
D	0.4929	0.4612	*0.5967	0.1355	1

Total mean value of the GRG = 0.5169,
* Optimum levels for GRG

Analysis of Variance (ANOVA) of experimental results

Analysis of Variance (ANOVA) was performed using statistical software MINITAB 17 on grey relational grade values to evaluate the influence of process parameters on multi-performance characteristics as shown in Table 7. ANOVA results indicate that four parameters such as Scrap (A), Grain Refiner (B), SiC (C) and Pouring Temperature (D) are the most significant that affect the multi-performance characteristics of the A518 alloy (p -value < 0.95) under 95% confidence levels. The multi-performance characteristics of the A518 alloy are mostly influenced by pouring temperature contributing 30.02% followed by Al-2.5Ti-0.5C- 18.41%, SiC- 8.92%, and as depicted in Fig. 6. Whereas, the scrap addition to A518 alloy have a less significant contribution to the performance characteristics.

TABLE 7. ANOVA of experimental results

Source	DF	SS	MS	F-Value	P-Value	Percentage contribution
A	1	0.0024	0.0024	0.2900	0.6020	1.20%
B	2	0.0369	0.0185	2.2200	0.1590	18.41%
C	2	0.0179	0.0089	1.0800	0.3770	8.92%
D	2	0.0602	0.0301	3.6200	0.0660	30.02%
Error	10	0.0832	0.0083			
Total	17	0.2006	0.0118			

Effect of process parameters on fluidity and mechanical properties

The fluidity and mechanical properties are mostly influenced by pouring temperature followed by grain refiner Al-2.5Ti-0.5C, SiC and Scrap. A linear relationship between pouring temperature and fluidity describes that increasing the pouring temperature causes delays the nucleation and growth of fine grains at the tip of the molten metal in the test channel; hence the fluidity length increases [15]. Also, the addition of SiC and grain refiner decreases the grain size and increase the fluidity of the A518 alloy. The green sand casting A518 alloy performance characteristics come under the criteria of “larger the better” type characteristic. The S/N ratios of the GRG for all 18 experiments were determined by the following equation.

$$S/N \text{ ratio (Larger the better)} = -10 \log \left[\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right] \quad (6)$$

The S/N ratio of the GRG for process parameters are shown in Fig. 6.

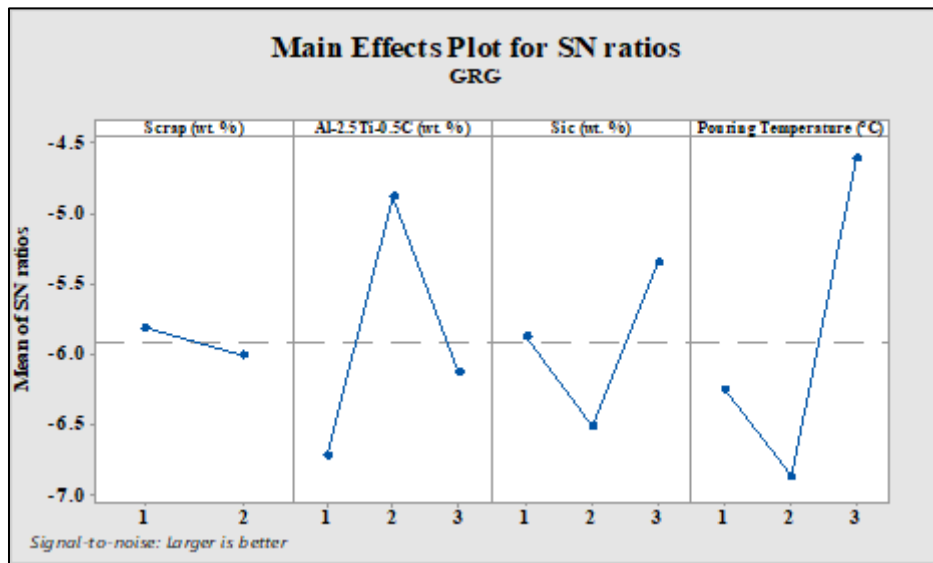


FIGURE 6. The S/N ratio of the GRG for process parameters

The experiment is performed at optimal process parameters found by the GRA, which consists of more globular grains as observed from optical microstructure analysis as shown in Fig. 7.

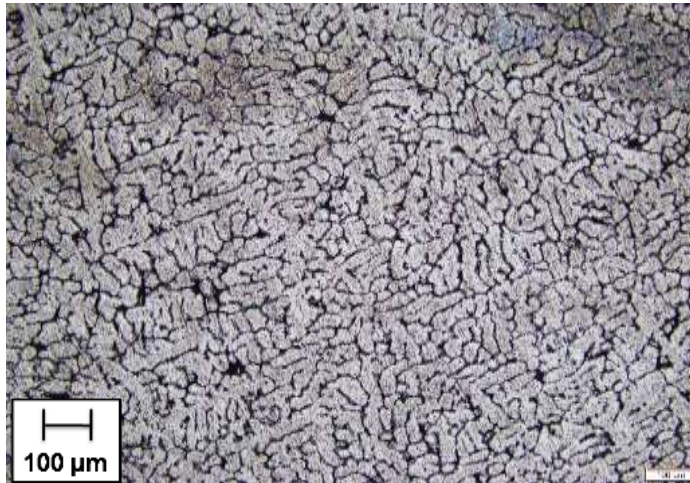


FIGURE 7. Optical Microstructure of the A518 alloy for 8 mm cross-section at the optimal parametric combination.

CONCLUSIONS

Based on the present investigation, the following conclusions have been drawn while optimization of sand-cast A518 alloy with variable process parameters by implementing Taguchi based Grey relational analysis:

1. It was observed from the Taguchi based GRA, an optimal parametric combination for A518 alloy obtained at the levels of Scrap-1.5, Al-2.5Ti-0.5C- 0.15%, SiC- 0.07%, Pouring Temperature- 800°C.
2. Based on ANOVA analysis, the pouring temperature has the leading process parameter contributing 30.02%, while grain refiner has an effect of 18.41%, and SiC at 8.92% on the performance characteristics of A518 alloy.
3. The casting obtained at optimal process parameters consists of more globular grains which were found by optical microstructure analysis and given appreciable fluidity and mechanical properties.

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