

Optimization of Hardness in CMT-Manufactured Al-5356 Walls Using Taguchi and ANOVA Techniques

Antar BOUHANK*, Youcef BELLAL, Abdesalem KAHLOUCHE

Research Center in Industrial Technologies – CRTI P.O.Box 64, Cheraga 16014 Algiers, Algeria

<http://doi.org/10.5755/j02.ms.45671>

Received 28 July 2026; accepted 1 September 2026

The effect of 3D printing parameters on parts hardness has been studied and optimized. Al-5356 alloy parts are manufactured using Cold Metal Transfer (CMT) technique. Torch traveling speed, gas flow rate, and current intensity are the essential CMT factors used. The main objective of the following study is to find and localize the hardness distribution from the bottom to top of CMTed parts and optimize the parameters in order to find out factors that give high hardness. To this end, the following factors have been chosen according to the Taguchi method of an orthogonal L9 design test. The latter method reveals highest optimization corresponds to the top zone, and the low one returns to the bottom zone. Whereas, zones between the top and the bottom have close values of optimized hardness. Besides the Taguchi method, the analysis of variance (ANOVA) was applied to statistically identify the effects of factors and model validation. The results found show that all factors have a significant impact on hardness. SEM images and microstructural studies confirmed the results of the hardness investigation using the Taguchi method. i.e., the top zone part contains more porosity than the bottom. The existence of the latter affects the hardness. In addition, microstructural investigation shows that the small grain size is located at the bottom, in contrast to the top due to the rapid solidification of aluminium and different heat distribution.

Keywords: cold metal transfer, aluminium alloys, Taguchi method, hardness.

1. INTRODUCTION

Cold metal transfer (CMT) is a welding method, developed by Fronious the Austrian company [1], based on the short-circuit transfer process with less thermal heat input. The filler wire is conveyed with a pulsating movement (pushing and pulling) into the melt pool [2, 3]. When the wire touches the process zone, it occurs a short-circuit and arc extinction, then the wire is mechanically pulled back, leaving a drop [4]. This operation is one CMT cycle. The latter restarts until the part is manufactured. Aluminium alloys are widely used as a filler wire due to their high corrosion resistance and lightweight [5, 6]. The place where these parts are placed is generally an aggressive environment. A high parts mechanicals property is thus required. One of the most mechanicals property is the hardness, especially of the last layer. Because the main aluminium alloy features, is very low melting point and rapid solidification. The latter affects density of the parts and reduces the mechanical properties [7]. The study of the hardness in the additive manufactured parts is of interest of many researchers. Shlyarov, V., et al. [8] have studied the hardness of low-alloy steel obtained by cold metal transfer in a magnetic field. They have found that the distribution of hardness over the part volume is heterogeneous and depends on the place of testing. The correlation between microhardness and microstructure of CMT Welded AA 7075 Al alloy, has been studied by Selvamani, et al. [9]. They have found that the hardness was decreased in the Weld Zone (WZ) compared to the Heat Affected Zone (HAZ). Shanker, Hari, and Reeta Wattal [10] have studied

the mechanical and microstructure characteristics of 7475-T7351 aluminium alloy joints welded by robotic cold metal transfer technique. It has been found that the base metal carries the maximum tensile strength. The weld metal (WM) has the lowest hardness. Another method to increase hardness is using network and design of experiments by varying welding parameters [11]. The latter is an effective method for optimizing the material weld quality. The same method has been used by Trembach, Bohdan, et al. [12]. The result was the arc voltage had the greatest influence on the microhardness value and the wire feed rate had a smaller effect. Finally, Bouhank and Bellal [13] have studied the effect of high current intensities on morphological and mechanical properties of CMTed parts, they have found high current intensities have a negative effect. This study, aims to improve the hardness in CMed parts and to localize the zone that needs the high optimization. To this end, the Taguchi method has been used as a statistical approach. This method allows us to predict the latter aim, a several printing parameters such as Torch traveling speed, gas flow rate and current intensity have been used to print aluminium parts.

2. ALUMINIUM ALLOYS IN CMT

The good properties of aluminium, like corrosion resistance and lightweight let it to be widely used in 3D printing by CMT technique, not ultra-pure aluminium (Al) but as alloy where the basic element is Al and the other alloying elements are generally silicon, zinc, manganese, magnesium and so on [14, 15]. Aluminium alloys, were

* Corresponding author: A. Bouhank
E-mail: a.bouhank@crti.dz

widely used in different industrial fields as well as aerospace, train building, automotive industries, and ship building [16]. The occurrence of anomalies such as porosity, rapid surface oxidation, and cracks still a big challenge in additive manufacturing of aluminium.

3. EXPERIMENTAL SET-UP

In order to manufacture aluminium parts, the Fronius welding source coupled with CNC table has been used as a printing equipment (see Fig. 1). The torch was positioned vertically relative to the substrate of aluminium, through which the filler wire is fed perpendicular and forward until it touches the melt pool where produces a short-circuit results in arc extinction [4]. Subsequently, the filler wire is mechanically pulled back, leaving a droplet. The torch moves, toward x axis with a constant speed, forming a bead. With to-and-fro movement respecting to the an increment with respect of the z-axis, the aluminium parts are printed after a while. The melt pool is protected with a shielding gas of argon (99.99 %) from oxidation effects. The filler wire used is AlMg₅Cr (A) of 1 mm section. The parts are walls of 100 mm × 50 mm × 3 mm. The chemical compositions of the Al alloys is presented in Table 1 [17].

Table 1. Chemical composition of the aluminium alloys used

	Element, wt.%							
	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti
min	92.9	0.05	—	—	4.5	0.05	—	0.06
max	95.3	0.2	0.1	0.4	5.5	0.2	0.25	0.2

Parameters used for manufacturing aluminium parts are listed in Table 2. Some parameters are fixed, variable factors are gas flow rates (6, 10 and 14 l/min), Torch traveling speed (1200, 1800 and 2400 mm/min) and current intensities (50, 70 and 90 A).

The CMT equipment is the welding machine TPS 500i type coupled to a Computer Numerical Control table (CNC) with three axes X, Y and Z (Fig. 1).

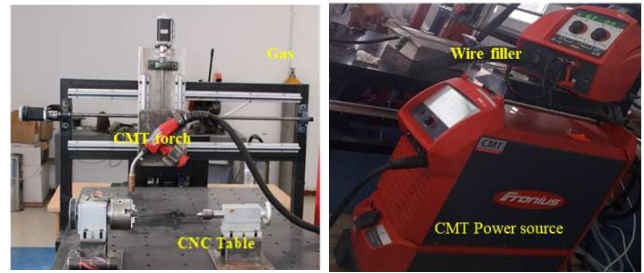


Fig. 1. Set-up of the CNC table-CMT-system

Table 2 .Process parameters used for CMT of Al-5356

Parameters	Values	Parameters	Values
Welding mode	MIG CMT	Gas (argon)	Variable
Operating mode	4 time	Current intensity	Variable
Material	Al 5356	Stick-out	10 mm
Diameter	1 mm	Filling increment	0.50 mm
Synchropulse frequency	0.5 Hz	Wire feed speed	6.4 m/min

The printed parts with CMT equipment are walls of 100×3×50 mm. Fig. 2 represents the quantitative analysis of the EDS spectrum . this figure shows that the CMTed parts components are primarily Al-Mg alloy with the following proportions: 89.81 of Al and 5.25 of Mg. Besides those elements, the oxygen peak is observed due to the aluminium oxide (Al₂O₃) layer which formed on the surface due to the environment and the rapid oxidation of the Aluminium [11, 12].

An X-ray diffraction (XRD) analysis was performed on Al-5356 samples prepared by the CMT method, the result is shown in Fig. 3. The most intense diffraction peak appears approximately at 38°, corresponding to the (111) crystal plane of aluminium (Al), indicating that Al is the main component of the alloy. Furthermore, the peaks observed at 45° correspond to the (002), (022), and (113) crystal planes of low intensity for Al. These peaks are coupled by the presence of peaks of nearly the same degree corresponding to the Al₃Mg₂ phase, indicating the presence of the aluminium matrix and the β phase (Al₃Mg₂) in the alloy.

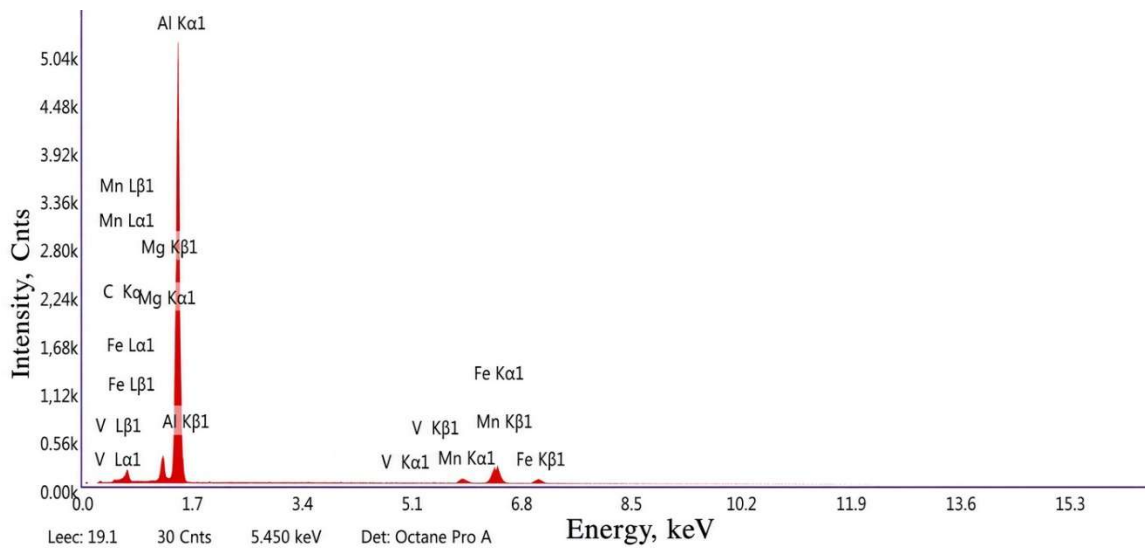


Fig. 2. EDS analysis data for manufactured Al-5356 parts

This phase is generally a strengthening phase in aluminium alloys, characterized by high hardness and strength.

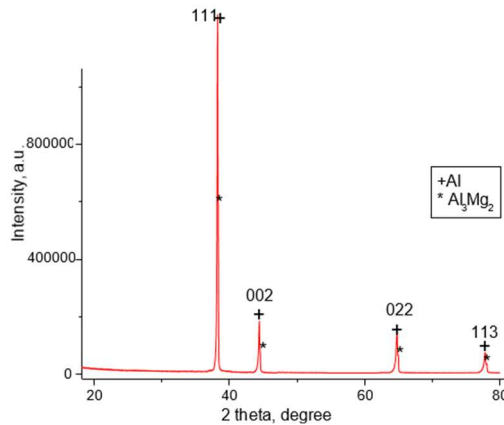


Fig. 3. X-ray diffraction patterns for manufactured Al-5356 parts

For the purpose of improving hardness inside aluminium parts. A cross section of walls has been taken as samples (see Fig. 4).

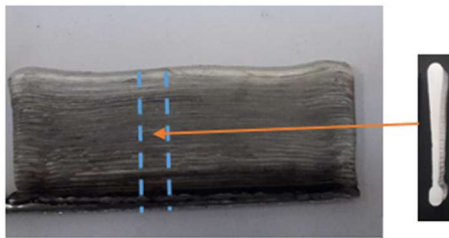


Fig. 4. Cross section of CMTed aluminium walls

3.1. SEM images and microstructure

To obtain more information about the entire specimen's surface (top, middle and bottom zones), Scanning Electron Microscope (SEM) images and microstructure have been used. Fig. 5 is the SEM image of parts at the three zones (top, middle and bottom). Three places for each zone were captured.

We can easily see that the top has more porosity and shrinkage than the middle and bottom because the initial layers are deposited directly onto a cold substrate that acts as a massive heat sink, inducing an ultra-fast cooling rate. Even though this rapid solidification of the aluminium traps micro-bubbles, it effectively restricts the growth of macropores. Conversely, as the build progresses upward, heat accumulates within the component, reducing the cooling rate. This prolonged liquid state of the melt pool allows microscopic gas bubbles to coalesce, expand, and develop into larger, more visible pores. Furthermore, shrinkage occurs because metals occupy less volume as a solid than they do as a liquid leaving behind surface depressions and internal shrinkage cavities especially in the last layers.

The analysis of microscope of inside walls after cutting and polishing. The microstructure of specimens, with different enlargements, shows a random granular structure with fine grain boundaries with a different grain size that are equiaxed grains (see Fig. 4). However, the top one (Fig. 6 a) has a large grain size compared to the others (Fig. 6 b and c), the same remark applies to the middle compared to the bottom.

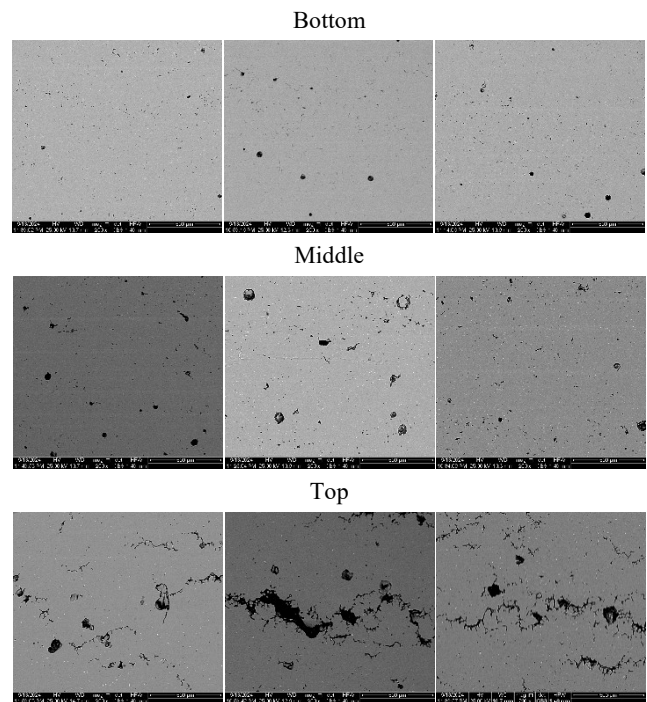


Fig. 5. SEM image of parts at the three zones (bottom, middle, and top)

3.2. Hardness measurement

Based on the above, we can see the existence of anisotropy in CMTed. For this reason, we have measured the hardness inside parts from the bottom to the top. The samples have been cut with a Secotom-60 laboratory micro-cutting machine from Struers.

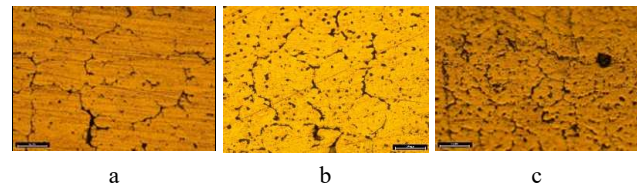


Fig. 6. Optical micrograph of aluminum walls: a – top; b – middle; c – bottom

The cutting operation is perpendicular to the torch movement. After that, samples were polished on an automatic struers Tegramin-30 with abrasive papers of several sizes: #500 up to #4000, finally followed by a state of finish by diamond suspensions: Dia-Duo 2 – 3 μm and Dia-Pro $\frac{1}{4}$ μm , spread out on a felt paper. The hardness test (Vickers) consists of applying a weight by pushing a diamond indenter into the sample, leaving a pyramid-shaped indentation (see Fig. 7).

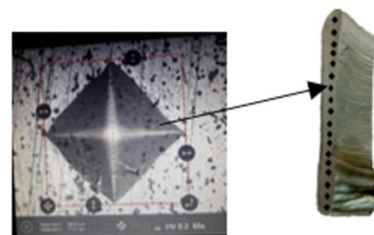


Fig. 7. Hardness measuring zones and pyramid-shaped indentation

Hardness tests on walls manufactured by CMT show that the bases are generally harder compared with the middle and top. Moreover, hardness in the top zones is dispersed due the rapid solidification of the aluminium (see Fig. 8).

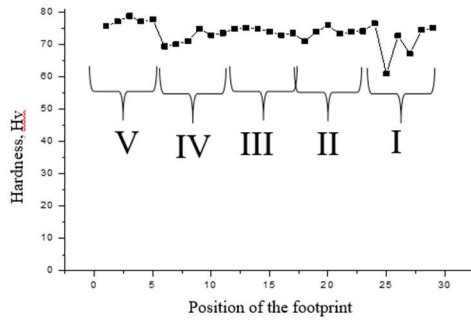


Fig. 8. Hardness measuring zones and pyramid-shaped indentation

The obtained results lead us to find out the optimized parameters that give us a high hardness. A numerical simulation is necessary. The domain has been divided into five subdomains, as shown in the figure above; these are numbered from the base of the part to the top.

3.3. Experimental design

In order to improve the hardness of manufactured parts, the Taguchi method is a powerful tool for optimizing productivity in the CMT process. This method develops high quality products in a short time with low cost [18] and also for identifying proper factors to achieve the optimum results [19]. The printing parameters mentioned before are fixed at three levels low, medium, and high to utilize Taguchi's a special orthogonal array L9 (9 experiments) and analysis of variance (ANOVA). This analysis is employed to know the significance of parameters to identify the percentage contribution of each factor effect. The design matrix of the experiment using the orthogonal array by the Taguchi method with Minitab software is presented in Table 3.

Table 3. Experimental layout L9 orthogonal array

N	Coded values			Actual values		
	F1	F2	F3	Intensity	Torch speed	Gas flow rate
1	1	1	1	50	1200	06
2	1	2	2	50	1800	10
3	1	3	3	50	2400	14
4	2	1	2	70	1200	10
5	2	2	3	70	1800	14
6	2	3	1	70	2400	06
7	3	1	3	90	1200	14
8	3	2	1	90	1800	06
9	3	3	2	90	2400	10

3.4. Results and discussion

The experimental values using the Taguchi method are tabulated in Table 4. The criterion "larger is better" has been used for optimal values determination of parameters. The ratio (S/N) (signal to noise ratio) for each process parameter level was also employed. The higher value of the latter, indicates better seal quality related to the optimum process parameter. The equation that describes the S/N ratio for evaluating higher quality is as follows:

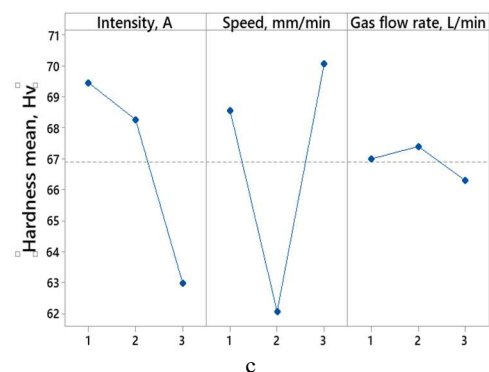
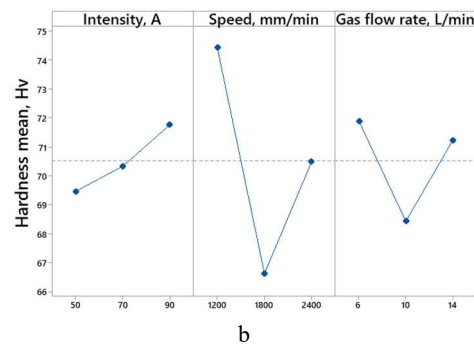
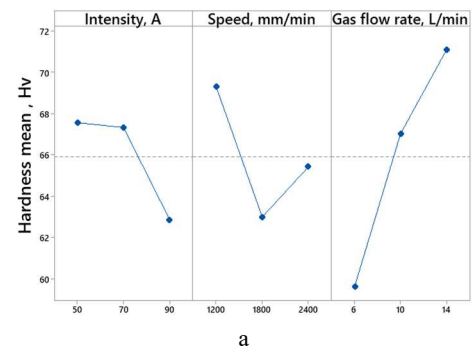
$$\frac{S}{N} = -10 \log_{10} \left(\frac{\sum_{i=1}^n \frac{1}{Y_i^2}}{n} \right), \quad (1)$$

where n is the number of trial test; Y_i is the total number of trials; i is the trial number.

Table 4. Experimental results, hardness (Hv) values and S/N ratio values

I Hv	I R/S	II Hv	II R/S	III Hv	III R/S	IV Hv	IV R/S	V Hv	V R/S
64.6	36.20	74.8	37.49	71.1	37.04	70.1	36.91	67.4	36.57
65.8	36.36	63.4	36.04	65.2	36.28	68.2	36.67	68.0	36.65
72.3	37.18	70.2	36.92	72.1	37.16	69.5	36.84	71.7	37.11
71.9	37.13	72.2	37.17	70.5	36.96	69.8	36.87	67.6	36.60
69.5	36.84	67.2	36.55	62.7	35.94	61.1	35.72	67.1	36.53
60.6	35.65	71.6	37.10	71.6	37.10	68.9	36.76	70.7	36.99
71.5	37.09	76.3	37.65	64.1	36.14	65.6	36.33	65.5	36.32
53.7	34.6	69.3	36.81	58.3	35.31	63.4	36.04	64.9	36.24
63.4	36.04	69.7	36.86	66.5	36.45	71.3	37.06	69.5	36.84

Executing the Taguchi method, with "the larger is better" option, we find the Fig. 9. From the figures, we can easily see the optimized values are calculated with the software and gives us the prediction values correspondingly to the larger is better (high hardness).



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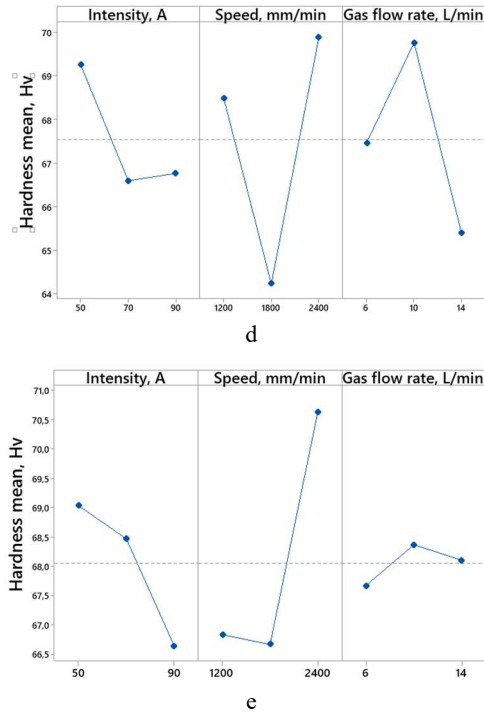


Fig. 9. Main effects plot for means of hardness for different zones (top to bottom): a – I; b – II; c – III; d – IV; e – V

In general, high hardness inside parts corresponds to the low current intensity, [13] have proved this result. By replacing the predicted value of hardness for each level with the mean of each experience response in the following equation to calculate the improvement rate:

$$\% \text{ improvement} = \frac{\text{Hardness}_{\text{optimal}} - \text{Hardness}_{\text{initial}}}{\text{Hardness}_{\text{initial}}} \times 100 \quad (2)$$

Table 5 contains the initial and optimal hardness values calculated by the Eq. 2.

Table 5. Optimization values of hardness

		Optimization, %	Zones
Initial	65.92	15.44	I
Optimal	76.1		
Initial	70.52	9.33	II
Optimal	77.1		
Initial	66.90	9.31	III
Optimal	73.13		
Initial	67.54	9.32	IV
Optimal	73.84		
Initial	68.04	4.57	V
Optimal	71.15		

Fig. 10 depicts the results obtained after improvement. It can be seen that the top zone needs more improvement (15.44 %) due to the rapid solidification of the aluminium (the last layers) which results more porosity. The bottom zone has low optimization because the latter is exposed to high heat, thus best melting, so low porosity (gas bubble escape easily). The middle zone has an overall optimization. This investigation led us to know the best parts zone from a mechanical property point of view. In the CMT technique, and after parts treatment, we should avoid the top and bottom zones to have an overall homogeneous hardness.

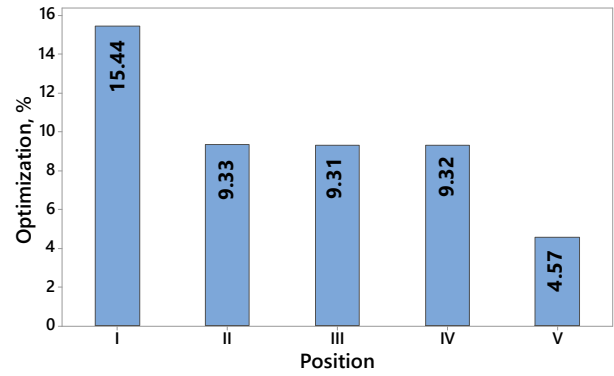


Fig. 10. Optimization in function of the position inside wall

3.5. ANOVA analysis

In order to estimate the relative importance of various factors, ANOVA is used for this reason. In addition, it is used to identify the contribution of each factor effect on the system response (hardness). Table 6 shows the analysis of hardness variance (ANOVA) calculated from the mean value at three levels at the top zone.

The observing Fisher values F_{obs} are very high comparing with the critical value (at 2-freedom degree and 5 % of risk) we can obviously conclude that, since all predictors are statistically significant ($p < 0.05$) and the error is very low, the model is statistically valid at the 5 % risk level. The same conclusion for all zone has been done.

The determination coefficient (R-Sq) for all zone is presented in Table 7.

Table 6. ANOVA Analysis results for the hardness of the top zone

Source	DF	Sum of squares	Mean squares	F	p
Intensity	2	9.4422	4.7211	1062.25	0.001
Speed	2	30.2022	15.1011	3397.75	0.000
Gas flow rate	2	0.7489	0.3744	84.25	0.012
Error	2	0.0089	0.0044		
Total	8	40.4022			

where DF are the degrees of freedom, F is the Fisher ratio used to compare variances; P is the critical probability at 95% confidence level.

Table 7. The determination coefficient (R-Sq)

	I	II	III	IV	V
R-Sq %	99.91	99.96	99.82	99.88	99.95

From the determination coefficient (R-Sq) shown in Table 7 below that equal more than 99 %, it implies that all CMT parameters were significant process parameters at the 95 % confidence level (5 % of risk).

4. CONCLUSIONS

From the outcome of hardness investigation inside CMTed parts of AlMg₅Cr (A), it is possible to conclude that:

1. The quantitative analysis of the EDS spectrum of the manufactured parts shows that the CMTed parts components are primarily Al-Mg alloy with the following proportions; 89.81 of Al and 5.25 of Mg. Besides those elements, the oxygen peak is observed due to the aluminium oxide (Al₂O₃) layer that formed on the surface due to the environment and the rapid oxidation of the aluminium.

2. The X-ray diffraction (XRD) analysis depicts that the most intense diffraction peak appears approximately at 38°, corresponding to the (111) crystal plane of Al, confirming that aluminium is the main component of the alloy. Furthermore, the peaks observed at 45° correspond to the (002), (022), and (113) crystal planes of low intensity for aluminium. These peaks are coupled by the presence of peaks of nearly the same degree corresponding to the Al₃Mg₂ phase, indicating the presence of the aluminium matrix and the β phase (Al₃Mg₂) in the alloy. This phase is generally a strengthening phase in aluminium alloys, characterized by high hardness and strength.
3. SEM images and microstructural studies confirmed the results of the hardness investigation using the Taguchi method. i.e., the top zone part (last layers) contains more porosity and shrinkages due the rapid solidification of Aluminium. The existence of the latter affects the hardness. In addition, microstructural investigation shows that the small grain size is located at the bottom, in contrast to the tops due to the rapid solidification of aluminium and different heat distribution.
4. The microscope analysis of inside walls shows a random granular structure with fine grain boundaries with a different grain size that are equiaxed grains. However, the top one has a large grain size compared to others, the same remark for the middle compared to the bottom.
5. Main effects plot for means of hardness for different zones shows that the optimal parameters at the top is (low intensity, low speed and high gas flow rate). This result is useful to avoid rapid solidification. At the bottom, the optimal parameters are (low intensity, high traveling torch speed, and medium gas), these parameters are good for ensure the rapid solidification of the bottom to avoid collapse and fusion of the matter of the walls.
6. The higher the value of the latter the ratio (S/N) (signal-to-noise ratio), indicates better seal quality related to the optimum process parameter.
7. The ANOVA results depict that all parameters are significant where intensity has a strong influence on the response (hardness), the highly significant, and the most influential factor. The gas flow rate is moderate but statistically valid.
8. That determination coefficient is greater than to 99 %, which implies that all CMT parameters were significant process parameters at the 95 % confidence level (5 % risk).

Acknowledgments

The authors gratefully acknowledge the support of the Directorate General for Scientific Research and Technological Development (DGRSDT). The authors also would like to thank Dr. Merabti Halim and Mr. Sami Debbache for their help and support.

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