

Experimental investigation on the effects of cooling system on surface quality in high speed milling of an aluminium alloy

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Abstract. Surface quality is often an important feature of industrial products, not only from the impact it has on the aesthetic aspect but also for the functional role of the parts. High quality surface increases corrosion resistance, assures a longer life cycle for the product and lowers the wear. For a machined part, surface quality is influenced by a series of factors such as the material of the part, the process type, tool geometry, cutting parameters or the cooling system. The choice of the cooling system is especially important, taking into account that the proper conditions will not only assure a superior surface quality, but will also lower the costs and reduce the environmental impact and health risks. The present study aims to investigate the performance of the cooling system and the effect of the cutting parameters on the characteristics of the surfaces resulted from high speed face milling of some parts made of Al 7050-T7451 aluminium alloy. Dry cutting conditions and minimum quantity lubrication (MQL) where used. The results were analysed using analysis of variance (ANOVA).

1. Introduction

Aluminium alloys are extensively used to manufacture products that are parts of the modern living. From household items, to automotive parts and structural elements for aerospace industry, aluminium alloys are the most appropriate choice due to their combination of high strength to specific weight ratio, very good machinability, resistance to corrosive processes and a large range of surface finishing.

Superior surface quality is a mean of increasing the aesthetic aspect of a product, to improve corrosion resistance and to a prolonged life cycle [1, 2]. Improvement of surface quality constitutes the subject of various studies [3] and different methods were approached to achieve it. The researches oriented toward the optimization of the cutting parameters used methods such as: design of experiments (Taguchi, response surfaces, etc.) [4, 5, 6], fuzzy logic [7, 8]. There are also different studies concerning the use of cooling and lubrication solutions: cryogenic [9, 10], minimum quantity lubrication (MQL) [11, 12] or nanolubrication [13]

The present study aims to investigate the performance of the cooling system and the effect of the cutting parameters on the characteristics of the surfaces resulted from high speed face milling of some parts made of Al 7050-T7451 aluminium alloy.

2. Experimental details

The experiments for this study were carried on a vertical machining center (Knuth Rapimill 700) using a face milling tool (Sandvik CoroMill) with 50 mm. The operations were performed on plates made of



aluminium alloy AA7050-T7451. This alloy is widely used in aerospace industry for structural parts due to its high strength, high resistance to corrosion and fatigue resistance. The chemical constituents of this material are presented in table 1.

Table 1. Chemical composition of the aluminium alloy.

Weight %	Al	Zn	Cu	Mg	Zr	Fe	Si	Mn	Ti	Cr	Other each	Others total
minimum	87.3	5.7	2.0	1.9	0.08	-	-	-	-	-	-	-
maximum	90.3	6.7	2.6	2.6	0.15	0.15	0.12	0.1	0.06	0.04	0.05	0.15

Table 2. Cutting parameters.

	Measurement unit	Values		
		-1	0	+1
Cutting speed, v_c	m/min	200		600
Feed per tooth, f_z	mm/tooth	0.13		0.26
Cooling method	-	MQL	Dry cutting	Compressed air

The experiments were organised according to a central composite design from response surface method. These designs are based on two level numerical factors, to whom categorical factors may be added. This will multiply the number of experiments by the number of combinations resulted from the categorical factor levels. Each numerical factor has five levels, as follows: two factorial levels (-1, +1) corresponding to the minimum and the maximum values of the factor, a central level (0) corresponding to the average of the factor, and the axial (or “star”) points ($-\alpha$, $+\alpha$) resulted by multiplying the factorial levels with α . The value for α is calculated to assure the rotatability of the design. The design space may be represented as in figure 1. The experiments for the central points are usually repeated by a number of times in order to get a good estimate for the experimental error.

For the current study, two numerical factors were considered – the cutting speed v_c and the feed per tooth f_z , respectively. The categorical factor was the cooling method during milling. Three types of cooling methods were deployed: MQL, dry cutting and compressed air. Each method was assigned as a level for the categorical factor. The physical values of the factors (the cutting parameters) are presented in table 2. Using this set-up the experimental plan contained 39 tests with factor combinations.

Certain aspects (responses) were monitored throughout this experimental research. Besides surface roughness (R_a) and surface hardness (HV), which are direct characterisations of surface quality, other features were also followed, such as: flatness deviation (FLD) and maximum temperature during the machining process (T).

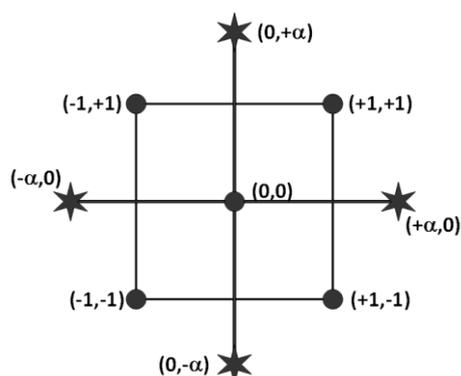


Figure 1. Distribution of the central composite design points.

Table 3. The experimental plan with the corresponding results.

Std. order	Run order	Cutting speed v_c [m/min]	Feed per tooth f_z [mm/tooth]	Cooling condition	Surface roughness R_a [μm]	Surface hardness HV	Flatness deviation FLD [μm]	Temperature T [$^{\circ}\text{C}$]
11	1	400.00	0.195	MQL	0.54	169.2	5	40.6
3	2	200.00	0.260	MQL	0.65	178.4	5	42.8
12	3	400.00	0.195	MQL	0.41	182.0	4	36.7
2	4	600.00	0.130	MQL	0.41	175.1	3	36.0
24	5	400.00	0.195	Dry cutting	0.39	173.7	3	48.8
37	6	400.00	0.195	Compressed air	0.49	176.6	4	47.3
35	7	400.00	0.195	Compressed air	0.54	178.8	4	47.3
28	8	600.00	0.130	Compressed air	0.70	162.3	2	55.8
18	9	117.16	0.195	Dry cutting	0.41	165.9	4	56.8
33	10	400.00	0.103	Compressed air	0.41	184.3	3	50.3
31	11	117.16	0.195	Compressed air	0.56	167.8	5	63.6
7	12	400.00	0.103	MQL	0.21	177.2	3	42.8
5	13	117.16	0.195	MQL	0.43	176.8	5	37.1
26	14	400.00	0.195	Dry cutting	0.23	191.0	6	48.0
38	15	400.00	0.195	Compressed air	0.42	159.0	2	46.3
4	16	600.00	0.260	MQL	0.57	174.3	2	45.4
6	17	682.84	0.195	MQL	0.34	180.1	4	39.9
23	18	400.00	0.195	Dry cutting	0.35	184.7	1	56.7
34	19	400.00	0.287	Compressed air	0.64	173.9	3	47.6
14	20	200.00	0.130	Dry cutting	0.56	169.9	3	48.6
25	21	400.00	0.195	Dry cutting	0.36	180.3	3	51.1
1	22	200.00	0.130	MQL	0.52	174.1	4	35.9
8	23	400.00	0.287	MQL	0.57	177.0	5	38.6
32	24	682.84	0.195	Compressed air	0.43	166.4	6	47.8
30	25	600.00	0.260	Compressed air	0.58	181.2	4	45.8
17	26	600.00	0.260	Dry cutting	0.51	184.0	6	53.4
16	27	200.00	0.260	Dry cutting	0.46	175.6	4	55.3
29	28	200.00	0.260	Compressed air	0.51	179.6	6	55.3
10	29	400.00	0.195	MQL	0.48	170.3	4	40.8
36	30	400.00	0.195	Compressed air	0.67	176.9	4	67.4
27	31	200.00	0.130	Compressed air	0.64	160.0	3	49.9
22	32	400.00	0.195	Dry cutting	0.34	160.3	3	48.6
15	33	600.00	0.130	Dry cutting	0.51	163.0	2	54.7
39	34	400.00	0.195	Compressed air	0.47	170.1	3	59.6
20	35	400.00	0.103	Dry cutting	0.31	161.6	2	65.1
21	36	400.00	0.287	Dry cutting	0.49	159.7	3	53.0
9	37	400.00	0.195	MQL	0.37	167.3	3	34.1
19	38	682.84	0.195	Dry cutting	0.36	194.6	2	48.1
13	39	400.00	0.195	MQL	0.50	168.6	2	37.4

Surface roughness was measured with a Mitutoyo Surftest SJ-210 while for the surface hardness a Metkon MH3 tester was used. Flatness deviation was determined using a TESA Micro-Hite 3D coordinate measuring machine. The temperatures were measured with a FLIR A325 infrared camera, which can deliver accurate results using the thermographic imaging method. The cooling conditions were changed by using different systems. For the minimum quantity lubrication method a SKF LubriLean Smart system was used, dry cutting was executed without any addition of coolant or

lubricant, while for compressed air the inner system of the milling machine was used, which is capable of supplying air at a pressure of 0.6 MPa. The experimental plan with the real life values of the influence factors is illustrated in table 3 together with the associated results (responses).

3. Discussion

The obtained results were analysed using analysis of variance (ANOVA). This is a statistical tool that allows to establish if the variation of the response could be determined by one or more significant factors. In ANOVA it is assumed that total variance can be decomposed in two terms: one related to the level of the influence factors and a term related to errors. F-tests are performed under the null hypothesis, larger values of F-ratios for one factor indicating its higher influence on the response [14].

In the following sections each response will be analysed based on the outputs of the ANOVA. A series of abbreviations will be used throughout the text, with the following meanings:

- df – degrees of freedom – each factor has the degrees of freedom equal with the number of levels minus one;
- SS – sum of squares represents the sum of the squares of the differences from the mean;
- MS – mean squares is the sum of squares (SS) divided by the degrees of freedom (df);
- F-ratio of a factor is calculated by dividing the factor MS to the error MS; a factor F-ratio larger than a critical value determines whether the factor is significant within a confidence level;
- p-value is used to determine if a factor is significant; for a 95% confidence interval, a factor that has a p-value below 0.05 is considered significant.

3.1. Surface roughness analysis

Roughness is an important indicator of surface quality for the manufactured parts. Lower surface roughness reduces wear, increases corrosion resistance and overall, it creates the premises for a longer life cycle of an industrial product.

In order to evaluate the effects of machining parameters on surface roughness R_a , ANOVA was carried and the results are presented in table 4. Only significant terms were taken into consideration and a mathematical model was derived.

Table 4. ANOVA table for surface roughness R_a .

Source	df	SS	MS	F-ratio	p-value
Model	3	0.16561	0.055202	5.66	0.003
Feed per tooth f_z	1	0.04272	0.04272	4.38	0.044
Cooling condition	2	0.12289	0.061443	6.30	0.005
Error	35	0.34146	0.009756		
Lack of fit	23	0.27268	0.011856	2.07	0.096
Pure error	12	0.06878	0.005731		
Total	38	0.50707			

The results of the test have revealed that the significant factor of influence for surface roughness is the feed per tooth and the cooling conditions. It was observed that the increase of the feed results in higher values of surface roughness. Some aspects concerning the influence of the cooling conditions on surface roughness can be observed from figure 2. The lowest surface roughness resulted from the combination of a small feed per tooth and MQL cooling. However, once the feed increases the effectiveness of the MQL system tends to decrease as it leads to surface roughness values higher than dry cutting. The poorest results were obtained for compressed air, for which surface roughness tends to be almost constantly higher than for the other two cooling systems.

The main effect plots for surface roughness with respect to the significant factors, based on ANOVA results, are presented in figure 3. The statistical analysis reveals that, overall, dry cutting conditions lead to lower values of surface roughness compared to the other options.

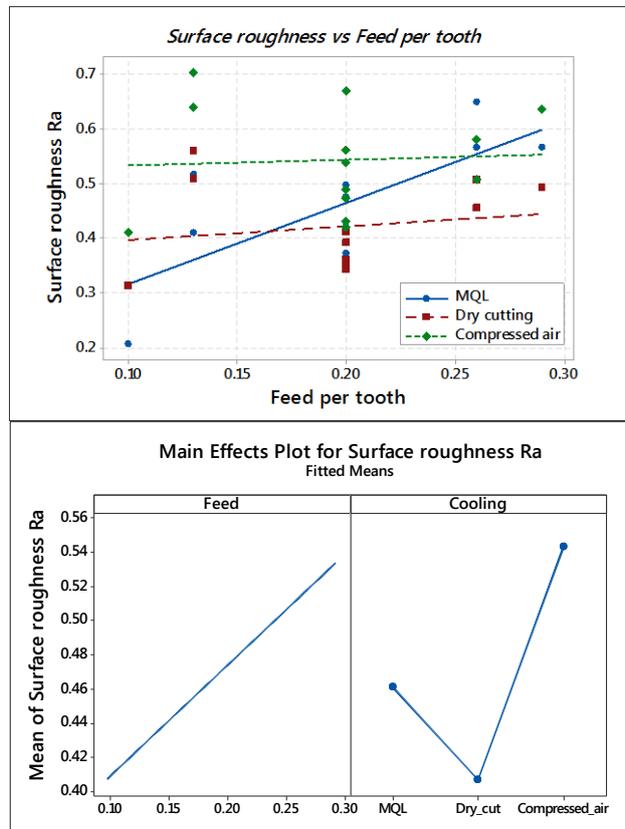


Figure 2. Surface roughness for various cutting parameters.

Figure 3. Main effects plots for surface roughness with respect to cutting parameters.

A series of regression equations were established between surface roughness and feed per tooth for the each of the cooling conditions:

$$\text{MQL: } R_a = 0.3342 + 0.649f_z \tag{1}$$

$$\text{Dry cutting: } R_a = 0.2800 + 0.649f_z \tag{2}$$

$$\text{Compressed air: } R_a = 0.4165 + 0.649f_z \tag{3}$$

3.2. Surface hardness analysis

The evaluation of surface hardness HV was carried using the same methodology used in the case of surface roughness R_a . However, unlike the former analysis, for surface hardness it was found that ANOVA revealed that none of the influence factors was significant. This could be explained by the fact that the variability of surface hardness values is very low. This can be easily observed from figure 4 which presents the interval plot of surface hardness against cooling conditions. For all the three cases the mean values of surface hardness were very close. Nevertheless, it is worth mentioning that in the case of MQL system the dispersion of hardness values is much lower than for the other cooling solutions.

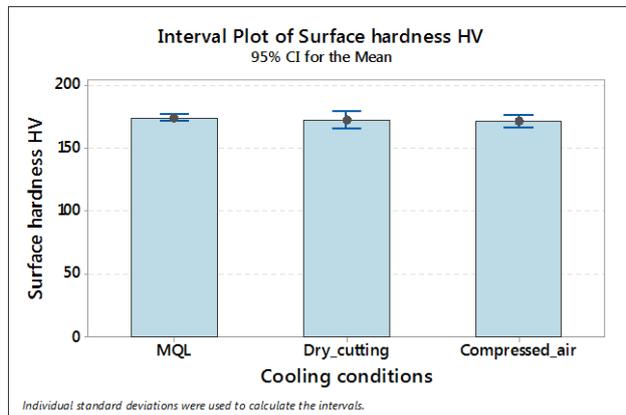


Figure 4. Interval plot of surface hardness for different cooling conditions.

3.3. Flatness deviation analysis

A similar analysis was carried also for surface flatness deviation. The graphical representations of flatness deviation against the cutting speed and feed per tooth, presented in figures 5 and 6, revealed that flatness deviation decreases with the increase of the cutting speed and with the decrease of feed, respectively.

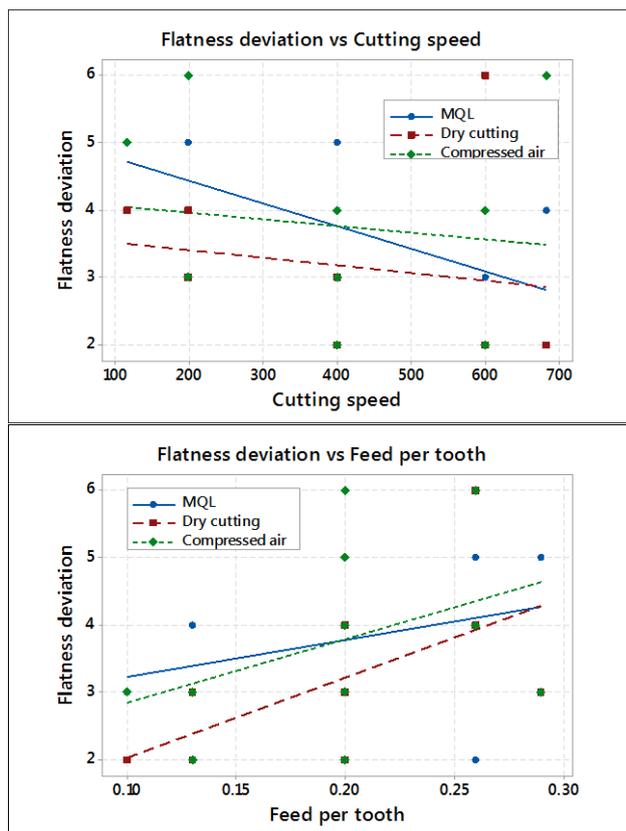


Figure 5. Evolution of flatness deviation with the cutting speed.

Figure 6. Variation of flatness deviation with the feed per tooth.

The results of the ANOVA test are shown in table 5, while the main effects plot for flatness deviation are illustrated in figure 7. Thus it was found that flatness deviation can be represented using a quadratic model in which the significant factors are the cutting speed (first and second order) and the feed per tooth (first order). The surface plot determined by this model is presented in figure 8. These results show that the increase of the federate (feed per tooth) increases the deviation from the planar

form. At the same time, the increase of the cutting speed is beneficial only to a certain level for which flatness deviation decreases to a minimum value.

Table 5. ANOVA table for flatness deviation FLD.

Source	df	SS	MS	F-ratio	p-value
Model	3	16.266	5.422	4.02	0.015
<i>Linear</i>	2	11.700	5.850	4.34	0.021
Cutting speed v_c	1	3.248	3.248	2.41	0.130
Feed per tooth f_z	1	8.452	8.452	6.27	0.017
<i>Square</i>	1	4.566	4.566	3.39	0.074
Cutting speed \times Cutting speed	1	4.566	4.566	3.39	0.074
<i>Error</i>	35	47.170	1.348		
Lack of fit	23	25.970	1.129	0.64	0.828
Pure error	12	21.200	1.767		
Total	38	63.436			

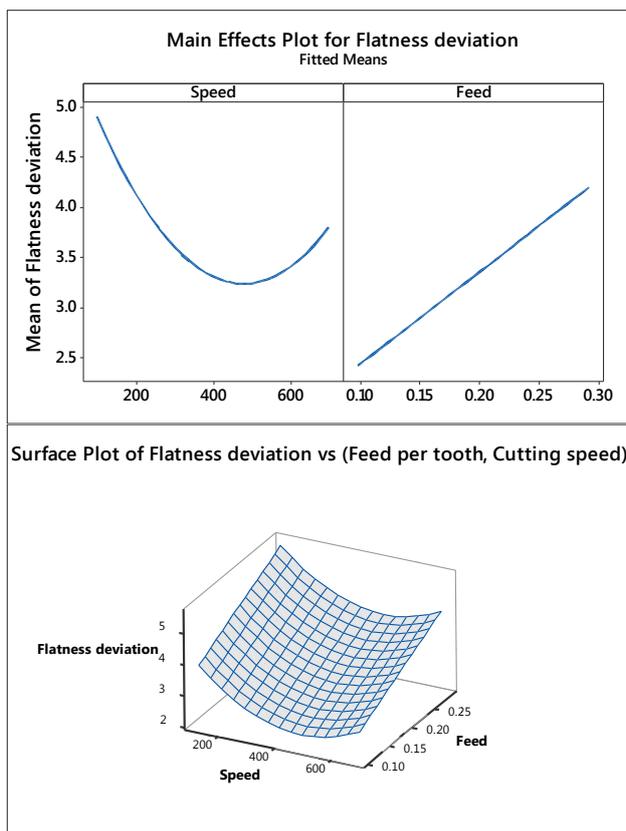


Figure 7. Main effects plot for flatness deviation with respect to cutting parameters.

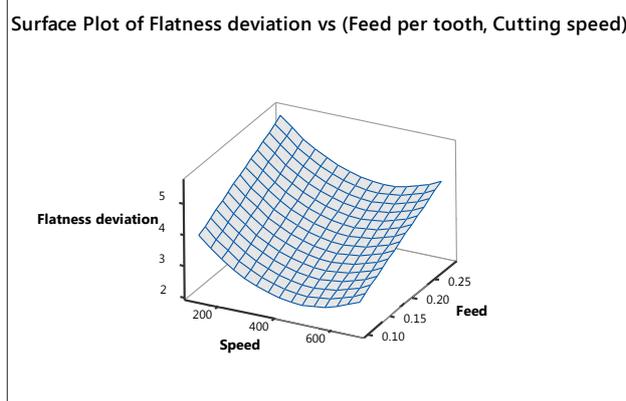


Figure 8. Surface plot for flatness deviation.

A mathematical relationship between flatness deviation and the cutting parameters can be written in the form of a quadratic equations, as follows:

$$FLD = 4.11 - 0.01111 \cdot v_c + 9.13 \cdot f_z + 0.000012 \cdot v_c^2 \quad (6)$$

3.4. Temperature analysis

Temperature is a factor with important implications on how the machining processes run. High level of temperatures is associated with distortions of the parts, lower tool durability, high levels of residual

stresses etc. As head development is an inherent consequence of the machining process, it is therefore important to control the temperatures by using different cooling systems. On the other side coolants are a perpetual problem linked to environmental aspects, health hazards or costs. This study was oriented towards the use of the most environmental friendly solutions. MQL uses small amounts of cooling liquids in the form of aerosols, dry cutting has the least hazardous impact, while compressed air uses only a pressurized flow of gas.

The temperatures were measured using a special infrared thermography camera. Pictures for each of the cooling solutions are presented in figure 9.

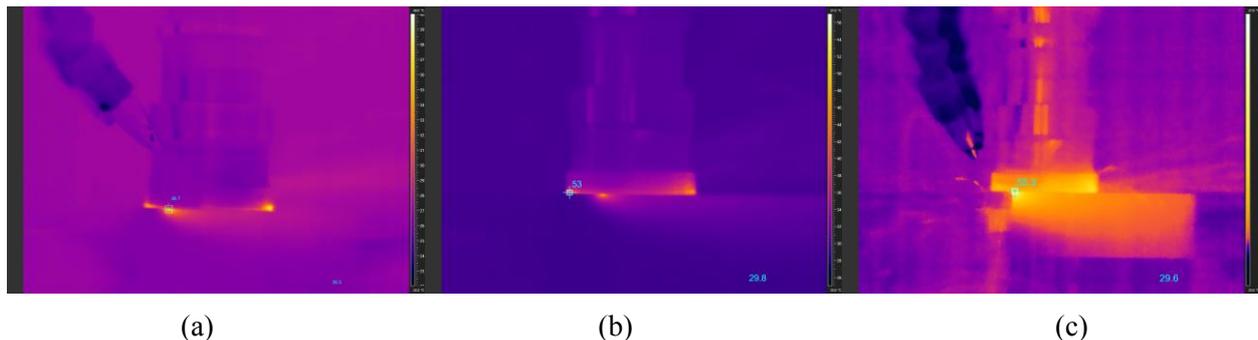


Figure 9. Infrared thermal imaging pictures for different cooling systems: (a) MQL, (b) dry cutting, (c) compressed air.

The most efficient cooling method was the MQL, due to the presence of the coolant even though it was only in small amounts, in the form of aerosols. For each use of the MQL system, the temperatures level was constantly below 40°C. The effectiveness of the compressed air in lowering the temperatures was, surprisingly, comparable to the dry cutting. For both systems the average temperatures were around 52°C, as it can be noticed from figure 10.

The results of the ANOVA test, presented in table 6, show that the considered conditions the only significant factor is the cooling solution. The above presented conclusions are also highlighted by the main effects plot for temperature presented in figure 11.

Table 6. ANOVA table for temperature T .

Source	df	SS	MS	F-ratio	p-value
Model	2	1625.5	812.75	28.36	0.000
Cooling solution	2	1625.5	812.75	28.36	0.000
Error	36	1031.7	25.66		
Lack of fit	24	589.3	24.55	0.67	0.809
Pure error	12	442.4	36.87		
Total	38	2657.2			

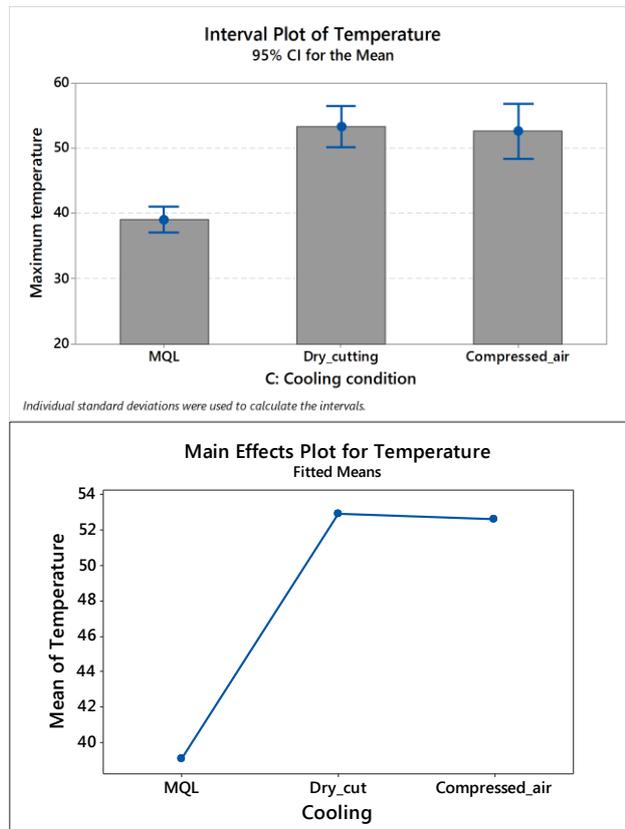


Figure 10. Maximum temperature distributions for different cooling systems.

Figure 11. Main effects plot for temperature.

4. Conclusion

The current study was oriented towards the implications of the cutting parameters, especially the cooling conditions, on the outcomes of the process. The main conclusions are formulated below.

- A central composite design was used to organise the research according to the response surface method.
- Surface roughness was mainly influenced by the feed per tooth and the cooling solution; a series of linear equations were derived based on ANOVA tests.
- No relationship was established between surface hardness and the cutting parameters, although it was observed that MQL has led to a tighter dispersion of the measured values.
- A quadratic equation was formulated for the variation of surface flatness deviation as a function of the cutting speed and the feed per tooth.
- The MQL system was the most efficient in lowering the temperatures measured during various machining conditions.

5. References

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