ANALYSIS OF RESIDUAL STRESSES, THERMAL STRESSES, CUTTING FORCES AND OTHER OUTPUT RESPONSES OF FACE MILLING OPERATION ON ZE41 MAGNESIUM ALLOY

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Abstract: The use of Magnesium alloy ZE41 nowadays has increased exponentially in the aeronautical industries for the manufacturing of certain high grade and complicated components. The reason for its perpetual usage is the fact that it has a very low mass to volume ratio and has very high hardness value, due to which it is used in aeronautical industries in order to improve the efficiency by decreasing the weight. Nowadays Magnesium based alloys are also finding their applications in biomechanics as biodegradable implants. It has proven to be a better alternative over Iron and Zinc based alloys and studies are conducted to improve its degradation rate and corrosive resistance. Also, it has proven to be a valuable alternative to Aluminum based alloys in industries due to its less density and high strength. That is why, in order to determine the best machining condition to manufacture these products, an analysis is carried out by dry face milling operation by keeping some input parameters under control and obtaining the resulting output parameters which are analyzed. Output responses which are analyzed are residual stresses, thermal stresses, cutting forces, chip thickness, surface roughness and material removal rate (MRR). These responses are analyzed in order to check the productivity and surface quality of the whole face milling process at set and controlled input parameters which are spindle speed, feed per tooth, depth of cut and tool diameter. These input parameters are initially decided and applied in the face milling operation due to which the resulting output responses are analyzed.

Key words: ZE41, Face Milling, Factors Influencing

1. INTRODUCTION

The applications of Magnesium alloys are vast. They are used in the fields of electronics, automobile, and aerospace due to its properties such as low density and high strength to weight ratio. Magnesium alloy, with a density of 1700 kg/m^3 is regarded as one of the lightest among the metallic materials because of the fact that Aluminum alloys are 35 % heavier than Mg alloys [1]. AZ31 is a Magnesium alloy which constitutes about 96% of Magnesium, 3% Aluminium and 1% zinc [2]. Dry milling is widely used in industrial manufacturing as a high performance cutting technology. Milling operation is often required to produce finished products [3]. Surface integrity in machined products nowadays is emerging as a new focus in machining research [2]. Guo et al., (2010) analyzed the surface integrity by high speed dry milling of Mg alloy. The findings of this study are high-speed dry milling operations which can be performed using PCD inserts safely with slight flank build-up and surface integrity characterized by low roughness [3]. Kaining Shi et al., (2015) conducted a dry face milling operation on a magnesium based alloy.Taguchi with grey relational analysis of experimental data carried out to determine an optimum combination of machining parameters for better surface roughness. Feed rate was regarded as the most dominant factor influencing surface integrity which was found out by the analysis of variance of grey relational grade. The optimum combination of process parameters were validated by validation experiments and the validations revealed that the Taguchi with grey relational analysis is an efficient method to determine available cutting parameters for a desired surface integrity during milling of magnesium alloy". "Grigoraş et al., (2015) analyzed the influence of milling parameters on surface roughness of AZ61A, a magnesium-Aluminum alloy [3]. The results of ANOVA analysis revealed that only speed and feed have a significant impact [7]. Zagórski et al., (2011) conducted end milling experiments on AZ31 and AZ91 alloy and they concluded that the best surface quality was achieved for a tool with a PCD cutting edge and the worst for a coated solid carbide tool and slightly higher roughness parameters were obtained for AZ31 than for AZ91 [8]. Yusup et al., (2012) presented an overview and comparison of the research work carried out during 2007-2011, that used evolutionary optimization techniques to optimize machining process parameters. Five techniques namely genetic algorithm, simulated annealing, particle swarm optimization, ant colony optimization and artificial bee colony (ABC) were considered. Among the various machining parameters that were optimized, surface roughness was the main parameter, followed by machining costs and material removal rate [9]. Tönshoff and Winkler [3] investigated the influence of different tool coatings on cutting force and surface roughness in turning magnesium alloys. They found PCD tools could achieve a superior behavior of the machined surface and the flank buildup could be avoided best by high cutting speed. Pu et al. [7] showed that increased cutting edge radius could lead to a deeper distribution of compressive residual stress and enhanced surface integrity on AZ31B Mg alloy under cryogenic conditions. Denkena and Lucas [8] found that an optimum set of process parameters could obtain a better surface quality in turning Mg-Ca3.0 alloy so that it could enhance its corrosion behavior. In order to promote product performance, improving the surface quality of machined parts is of greatest importance. It has been shown that process parameters, such as cutting speed, feed rate, and depth of cut greatly influence surface integrity [10–12]. In general, the Taguchi method was widely used in experimental planning and parameter optimization for machining processes. Hasçalık and Çaydaş [13] applied Taguchi method to select the optimal machining parameters for improving surface roughness and prolonging tool life, respectively, in turning Ti-6Al-4V alloy. Kilickap [14] studied the optimal combination parameters for minimizing burr height and surface roughness, which were determined by using Taguchi design. Meanwhile, the response surface method was employed to predict burr height and surface roughness in drilling Al-7075. Erkan et al. [15] carried out Taguchi method and GONNs to evaluate machinability of milling composite materials. The results of ANOVA analysis was used to show that the cutting speed is the most significantly factor affecting surface roughness. Although Taguchi method can be applied to find the optimized process parameters, it is still difficult to handle the multi-objective optimization problem involved. In order to improve the multiple quality characteristics, the Taguchi with grey relational analysis was currently regarded as an efficient optimization method in various machining processes [16–26]. In this present study, to determine the behavior of output responses by taking some input parameters into consideration and determine the best parameters which will give the most efficient response to the set input parameters.

2. EXPERIMENTAL AND MEASUREMENT PROCESS

To carry out the face milling of ZE41 Die Cast Magnesium alloy, there were many experiments performed through different parametric conditions and the experiments performed were done under the required range of the process. they are dry face milling(by CNC milling machine, Make BFW model Gaurav), cutting forces calculation(by dynamometer, Make Kistler, Make 9257B), Residual stress calculation(by XRD and analytical method), thermal stress calculation(by infrared thermometer), chip thickness calculation(by image analyzing software) and surface roughness(by Talysurf). Material Removal Rate (by difference between initial and final by initial multiply by density).The machine used for face milling operation is a 3 Axis Vertical Milling CNC machine with maximum axis feed of 10000 mm/min and a maximum spindle speed of 8000 RPM. The inserts used are 0.8mm nose radius carbide cutting inserts. To control the input parameters, spindle speed, feed rate, tool diameter and depth of cut were taken into consideration.

Table 1. Properties of ZE41 alloy

Properties	Tensile strength, [MPa]	Modulus of elasticity, [GPa]	Poisson's ratio	Elongation [%]	Brinell hardness [BHN]	Density, [Kg/m^3]	Thermal expansion coefficient, [μm/m̊C]	Melting point, [̊C]
Values	218	44.12	0.35	4.50	55-70	1700	15.1	532-638

Table 2. Process parameters and levels

S. No	Process Parameters	Units	Level 1	Level 2	Level 3
1	Spindle speed	rpm	7000	7500	8000
2	Feed per tooth	mm	0.6125	0.634	0.645
3	Depth of cut	mm	1.5	2.0	2.5
4	Tool diameter	mm	20	25	30

Table 3. Output response

Si. no	Spindle speed	Feed per tooth	Depth of cut	Tool diameter	Surface roughness	Chip thickness	Resultant cutting force	Residual stress	Thermal stress
	[rpm]	[mm]	[mm]	[mm]	[µm]	[µm]	[N]	[N/m²]	[N/m²]
1	7000	0.6125	1.5	20	2.1794	330.1	834.0791919	26596401.94	7994544
2	7000	0.6125	2	25	2.1476	431.04	1210.714107	34841716.89	9993180
3	7000	0.6125	2.5	30	3.0448	491.73	1342.193141	-18614190.72	12658028
4	7000	0.634	1.5	20	2.1881	511.01	860.6629923	59934491.25	13990452
5	7000	0.634	2	25	2.1687	539.51	1291.877661	48182455.17	16655300
6	7000	0.634	2.5	30	3.1008	572.92	1410.706852	-29779123.45	19320148
7	7000	0.645	1.5	20	2.1905	556.97	904.3851903	41034134.64	21318784
8	7000	0.645	2	25	2.1798	697.94	1330.741711	42783845.17	24649844
9	7000	0.645	2.5	30	3.2348	760.74	1582.119221	159235647.4	26648480
10	7500	0.6125	1.5	20	1.4434	796.03	927.1384742	28467766.43	20652572
11	7500	0.6125	2	25	2.6987	817.59	1142.513625	171067410.4	23317420
12	7500	0.6125	2.5	30	2.9917	832.83	1794.256525	-180587813.7	25316056
13	7500	0.634	1.5	20	1.5587	722.8	949.0319116	133789660.6	27980904
14	7500	0.634	2	25	2.8298	820.48	1236.583624	50655166.37	30645752
15	7500	0.634	2.5	30	3.0564	923.48	1873.440283	-48944494.68	34643024
16	7500	0.645	1.5	20	1.7002	779.92	1001.954631	56647503.86	37974084
17	7500	0.645	2	25	2.9792	786.57	1429.277654	87230583.74	39972720
18	7500	0.645	2.5	30	3.1769	946.15	2075.096383	31457249.75	43303780
19	8000	0.6125	1.5	20	1.6616	986.03	1019.235684	95435578.5	29979540
20	8000	0.6125	2	25	2.2215	1118.95	1557.17828	199293776.9	31978176
21	8000	0.6125	2.5	30	3.9211	1224	2132.043329	-199390229.9	34643024
22	8000	0.634	1.5	20	1.8779	1044.16	1056.07481	52408018.35	37974084
23	8000	0.634	2	25	2.3761	1140.42	1678.061682	185370585.3	40638932
24	8000	0.634	2.5	30	4.0132	1222.9	2195.305049	-151657008.7	41971356
25	8000	0.645	1.5	20	1.9456	1079.2	1075.769515	92319047.55	44636204
26	8000	0.645	2	25	2.5007	1127.13	1702.264317	187402841.8	46634840
27	8000	0.645	2.5	30	4.1131	1233.26	2287.73272	4371931760	47967264

3. RESULTS AND DISCUSSIONS

All the output responses which were recorded and observed through the set input parameters are discussed and a conclusion is made in accordance to these responses.

3.1 Influence by residual stresses

In the figures 1-4 an unusual characteristic is observed about the residual stresses. According to basic knowledge, residual stresses must increase with an increase in machining parameters like spindle speed, feed rate, depth of cut and tool diameter, but in this case it is partially decreasing and then increasing at irregular intervals. There was no such perfect explanation to as to what was causing this abnormal behavior of these stresses except one. The theory behind this anomalous behavior of residual stresses goes to the physical properties of the alloy. Since the alloy used here is ZE41 Magnesium alloy, it has a very low melting point (about 532-638 degree Celsius) and during the face milling operation, the alloy was under machining, it was constantly heating up and was nearing to its recrystallization temperature ($0.5T_m$) and this causes the grain structure of the material to alter. As a fact that recrystallization temperature was not achieved but a term called as 'recovery' temperature of the material was achieved which happens due to annealing. Annealing is a process of heating the material and leaving it out for a longer duration. During this time, recovery is achieved at lower temperatures while recrystallization temperature is achieved at high temperatures. Since during the recovery process, the grain structure does not change, but the defects that were initially present in the material absorbs the forces which are imparted on it and hence the residual stresses also increases in the material. But if the process is carried out for a longer duration, these forces which were trapped inside the defects are relieved due to the increase in temperature and hence the residual stresses are also minimized. Hence this is the only theory that explains this anomalous behavior of residual stresses.That is why the process which takes a lot of time (at low feed rate and spindle speeds), the residual stresses will initially increase and then decrease. This is observed in figures 1, 3 and 4 whereas in figure 2 since the feed per tooth is very high, there is no enough time for the material to absorb and emanate these forces in the given interval of time.

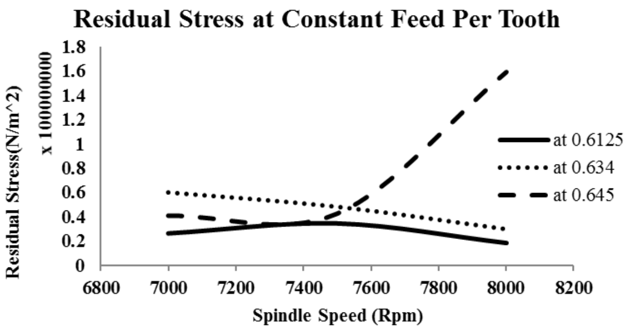

Fig. 1. Graph between residual stress and spindle speed at constant feed per tooth

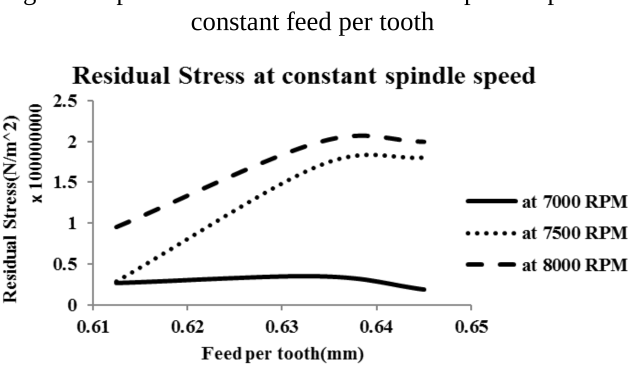

Fig. 2. Graph between residual stress and feed per tooth at constant spindle speed

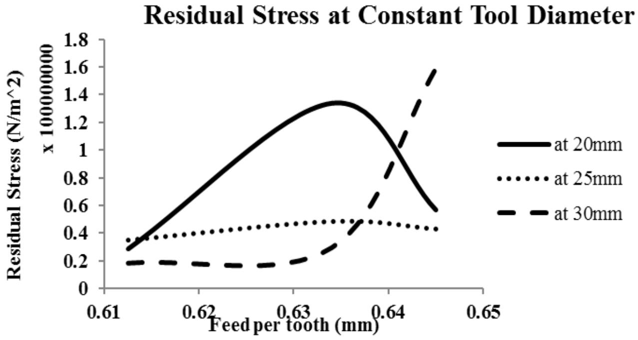

Fig. 3. Graph between residual stress and feed per tooth at constant tool diameter

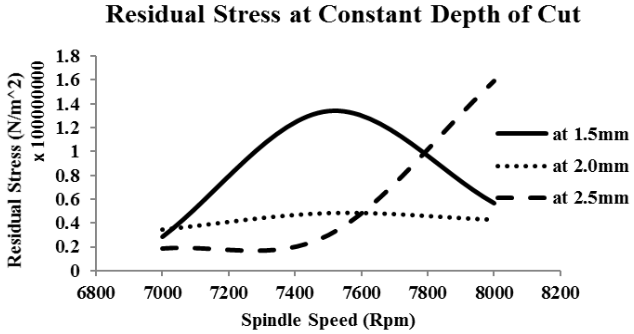

Fig. 4. Graph between residual stress and spindle speed at constant depth of cut

3.2 Influence by thermal stresses

In Figure 5 it is observed that with increase in feed per tooth, the thermal stresses are increasing, while keeping the spindle speed constant at 7000, 7500 and 8000 rpm respectively. It can be observed that there is a huge difference between the thermal stresses at 7000 rpm and 8000 rpm. Hence it can be inferred that by increasing the spindle speed, the thermal stresses also increase quite linearly. In Figure 6 it is observed that at constant feed rate, the thermal stresses are increasing with increasing spindle speed. It is observed that there is a huge difference in the thermal stress values at a feed rate of 0.6125 and 0.645 respectively, while the values at 0.634 are increasing constantly with no fluctuation. Hence it can be inferred that by increasing the feed per tooth, the thermal stresses also increases.With contrast to the above figures, when the depth of cut is kept constant with increasing feed per tooth (Figure 7), the thermal stress values have a really high positive slope which was not the case in the previous graphs. The lines are compact to each other and a slight amount of fluctuation is observed. Hence it can be inferred that by increasing the depth of cut, the thermal stresses increases drastically. Just in contrast to the previous figure, here (Figure 8) the characteristics are also similar in nature where the tool diameter is kept constant at increasing spindle speed values. There are negligible amount of fluctuation which are observed in line at 20mm depth of cut. Overall, it can be concluded that by increasing the tool diameter, the thermal stress values are also drastically increasing.

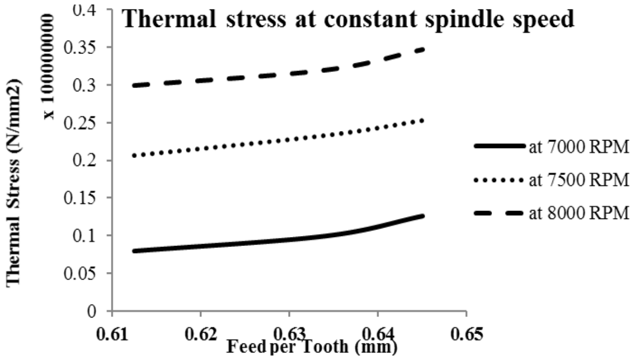

Fig. 5. Graph between thermal stress and feed per tooth at constant spindle speed

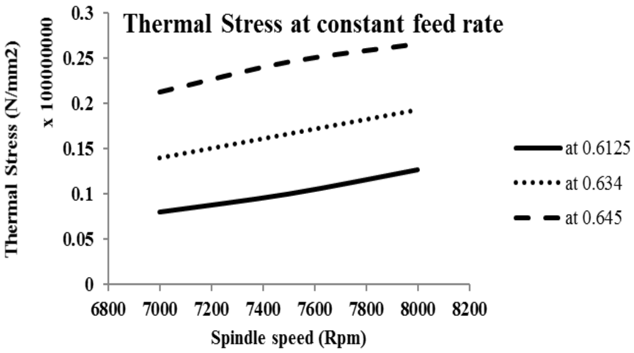

Fig. 6. Graph between thermal stress and spindle speed at constant feed per tooth

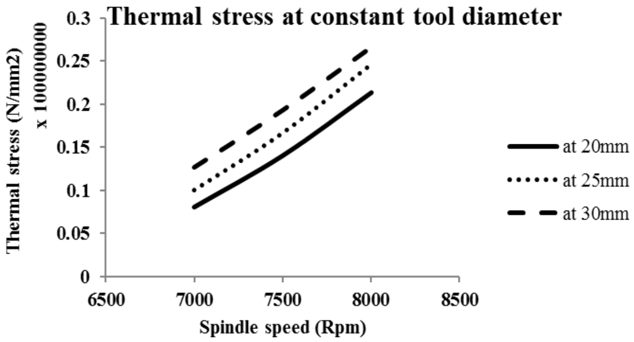

Fig. 7. Graph between thermal stress and spindle speed at constant tool diameter

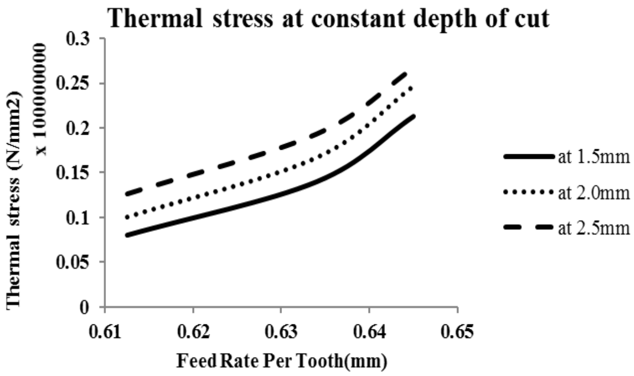

Fig. 8. Graph between thermal stress and feed per tooth at constant depth of cut

3.3 Influence by chip thickness

In the Figure 12 it observed that at constant spindle speed and increasing feed per tooth, the chip thickness overall increases while at a spindle speed of 7500 rpm, the chip thickness appears to be constant all the time but there is a slight increase in its slope value. Hence it can be concluded that by increasing the feed per tooth, the chip thickness values increase constantly. However in figure 11, it is noticed that at constant feed per tooth and increasing spindle speed, the chip thickness values do not increase a lot as they did in the previous figure but instead, they are plotted pretty close to each other and the slope values of each spindle speed lines are not significantly high. Hence it can be inferred that there is not much significant change with increasing spindle speed. The reason that the graph is increasing in nature here is due to the fact that other parameters like depth of cut and tool diameter are also varying and altering the nature of the graph.In contrast to the above two figures, the Figures 11 and 12 have shown similarity in nature except a slight fluctuation in its curves. In Figure 9, it is observed that at constant depth of cut and increasing spindle speed, the chip thickness do increase but in a very odd manner. At a depth of cut of 2.0mm, the line is perfectly linear with a slight and negligible fluctuation while the other two lines at 1.5mm and 2.5mm respectively bulge inwards and outwards respectively. While in Figure 10, it is observed exactly the same in Figure 9 but only with a little more variation and fluctuation. Here the tool diameter is kept constant while the feed per tooth are increasing in nature. Hence it can be inferred from both figures (Figure 9 and Figure 10) that both depth of cut and tool diameter affect the chip thickness in a similar fashion and are both proportionally related to the chip thickness value.

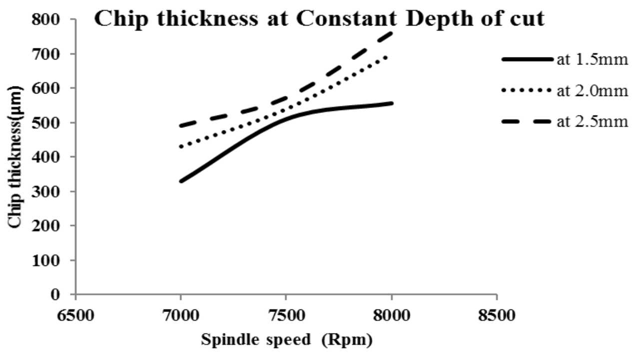

Fig. 9. Graph between chip thickness and spindle speed at constant depth of cut

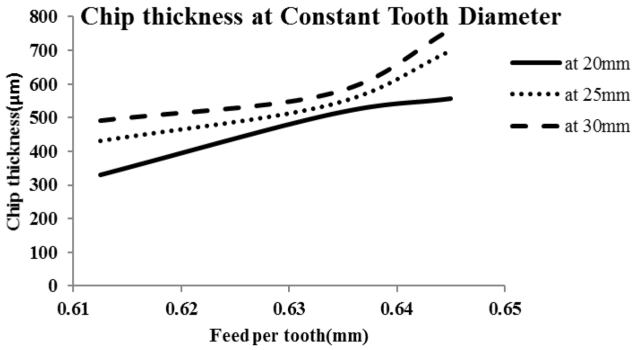

Fig. 10. Graph between chip thickness and feed per tooth at constant tooth diameter

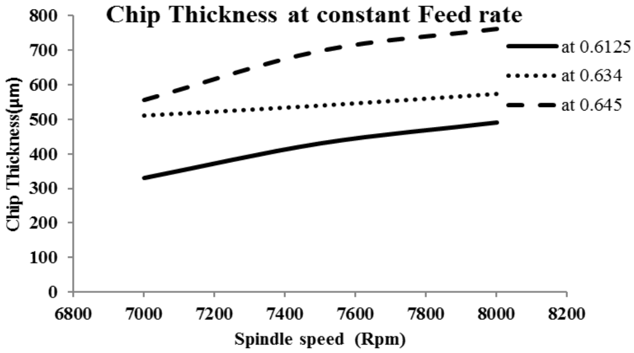

Fig. 11. Graph between chip thickness and spindle speed at constant feed per tooth

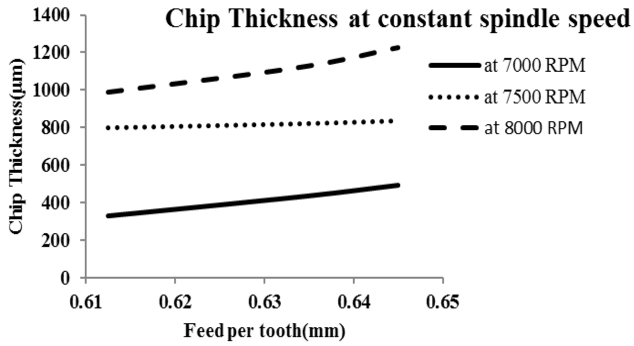

Fig. 12. Graph between chip thickness and feed per tooth at constant spindle speed

3.4. Influence by cutting forces

In the Figures 15 and 16, it is observed that the cutting forces are increasing. In Figure 15 it is observed that at increasing feed per tooth, the cutting forces are increasing while keeping the spindle speed constant. In contrast to this, the Figure 16 shows quite unusual characteristics. It displays that the forces are quite close to each other at constant feed per tooth and increasing spindle speeds. Hence it can be inferred that the cutting forces are closely linked with spindle speed than feed per tooth. In contrast to the above figures, the Figures 13 and 14 show similar characteristics with a slight variation in it are plotting of these lines. By observing these two graphs carefully, it can be inferred that both constant depth of cut and tool diameter are proportionally related to the cutting forces at increasing spindle speeds and feed per tooth respectively.

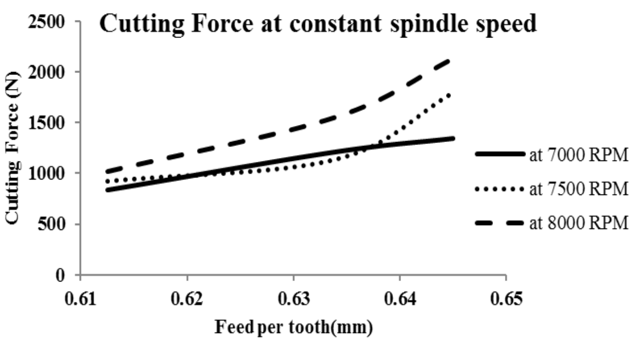

Fig. 13. Graph between cutting force and feed per tooth at constant spindle speed

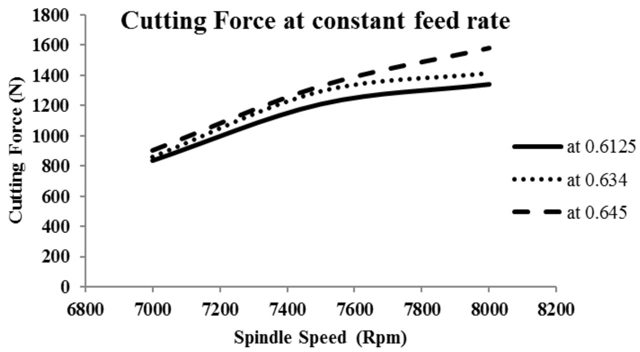

Fig. 14. Graph between cutting force and spindle speed at constant feed per tooth

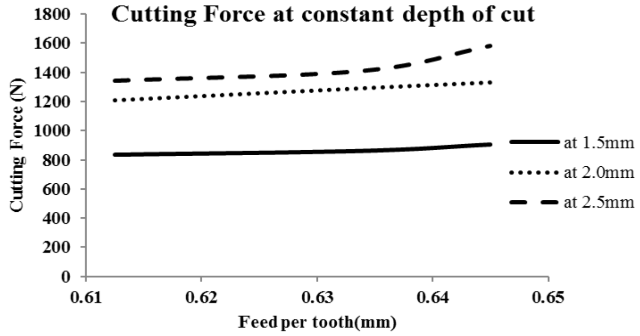

Fig 15. Graph between cutting force and feed per tooth at constant depth of cut

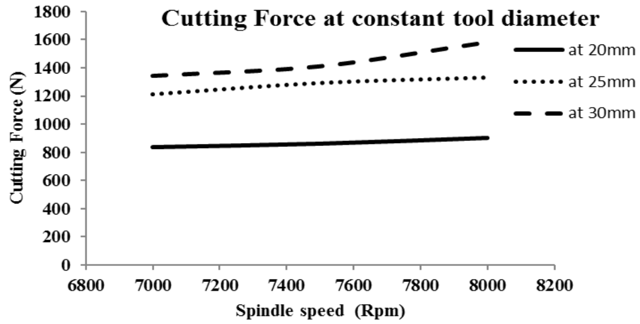

Fig. 16. Graph between cutting force and spindle speed at constant tool diameter

3.5. Influence by surface roughness

By observing the figures 17-20, it is observed that spindle speed does not have a noticeable effect on surface roughness (Figure 17) but feed per tooth does have a drastic alteration on the surface roughness values. With an increase in feed per tooth, the surface roughness also increases, hence deteriorating the surface finish of the alloy. The same can be concluded for Figure 19 and 20 where keeping the depth of cut and tool diameter constant also have a same effect on the surface roughness, i.e. it decreases the surface smoothness and hence separate surface finishing techniques like grinding and honing are to be used in order to improve the surface finish. Since there are about 5 output parameters that were studied and recorded by keeping 4 input parameters under observation and control, the following results are drafted and discussed: overall, the residual stresses are increasing in nature despite its anomalous behavior discussed before.

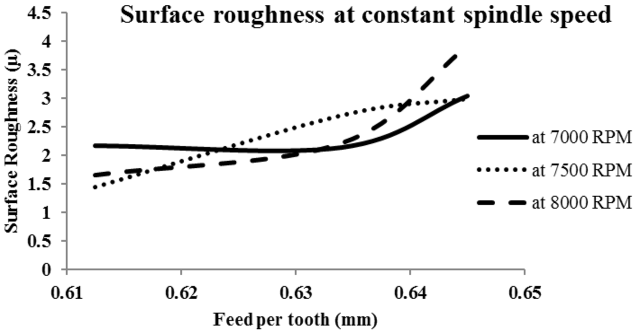

Fig. 17. Graph between surface roughness and per tooth at constant spindle speed

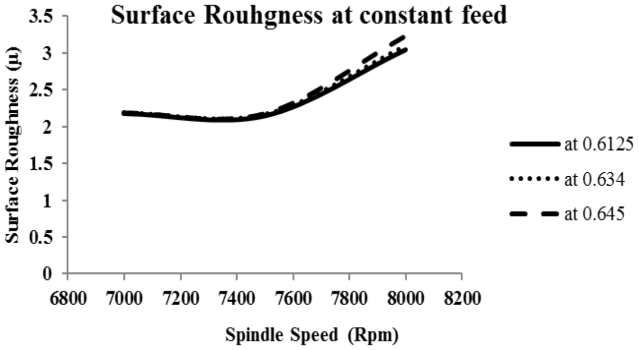

Fig.18. Graph between surface roughness feed and spindle speed at constant feed per tooth

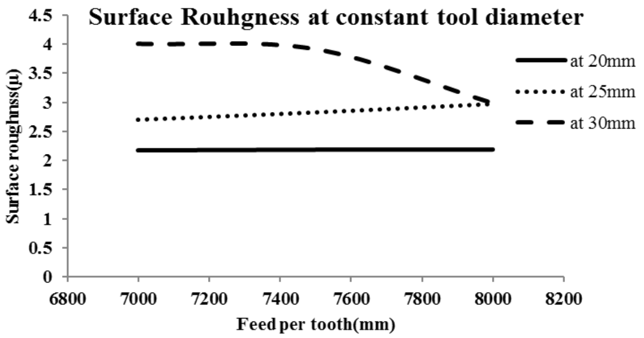

Fig.19. Graph between surface roughness and feed per tooth at constant depth of cut

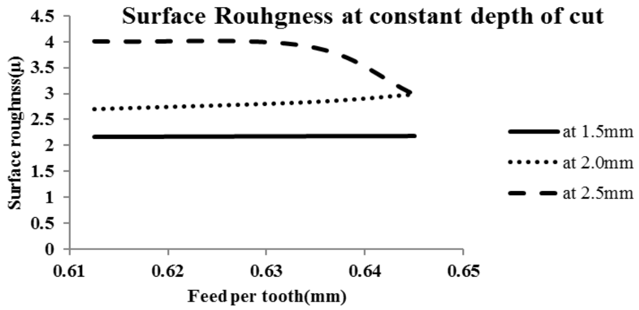

Fig. 20. Graph between surface roughness and spindle speed at constant tool diameter

Hence it is not safe for the finished product to contain high magnitudes of Residual stresses which can easily decrease its performance and life during its application. Hence the product must be made free of maximum amount of residual stresses before any of its application like shot peening or heat treatment at low temperatures. During the observation of thermal stresses, it was noted that the thermal stresses increased with an increase in the input parameters. Hence the tool and work piece interface temperature was high due to which it can easily affect the tool life and at the same time the integrity of the surface of the material which would have undergone some thermal changes due to the fact that ZE41 has a very low melting point. Hence extra precaution must be taken in order to machine this alloy with sufficient coolant which will provide some insulation and decrease the chance of deteriorating the surface integrity of the material. The cutting forces which were calculated with the help of a dynamometer were not significantly larger in values. The largest cutting force recorded was up to 2100N, which can be easily bared by the alloy. Hence the forces will not affect the integrity of the material and is in the allowable range. This also ensures the safety of the cutting tool and also it will not affect the performance of the material after its production. The only reason to be worried about here is the formation of residual stresses which will be stored inside the material. But those stresses can be taken care of by shot peening. The chip formed during the process were collected and studied to calculate its thickness. The results produced were positive and from those results, it can be concluded that the increase in chip thickness with increase in input parameters provides an excellent productivity and with the time of cut limited to only 14-15 seconds, it provides a good machining rate as well. But with increased chip thickness, the risk of decrease in tool life is also present. Hence it can be concluded that with the given data about chip thickness, it provides excellent productivity. On the other hand it is clear that an increase in feed per tooth, the surface finish of the material is likely to reduce. Hence the surface roughness with an increase in input parameters also increases and deteriorates the surface integrity of the material. Hence it is clearly advised to take the material for proper surface finish operations just after the machining process. The overall assessment of these results convey that the input parameters used are sufficient for a productive machining but due to the residual stresses imparted during the machining can affect the product's quality and life during its application.

4. CONCLUSION

The following are the output responses that were obtained and studied during the dry face milling operation of ZE41 mMagnesium alloy. These output responses are very important during the machining of this alloy. The residual stresses obtained are not significant to any of the input parameters that were taken into consideration. There were some input parameters that significantly altered the residual stresses, but due to its physical properties the stresses behaved in a different way. The anomalous behavior of residual stresses at high input parameters. Thermal stresses obtained were significant to all the given input parameters and it gradually increases with an increase in the input parameters. Hence the rise in thermal stresses must not be too high as it can easily decrease the tool life. The cutting forces also gradually increased with an increase in input parameters. These forces should be kept under control as they can impact the cutting tool. The chip thickness only depended significantly upon feed per tooth and depth of cut while the other two input parameters (spindle speed and tooth diameter) did not have a noticeable effect on the response. The surface roughness significantly depended upon all the input parameters and was intensively altered with an alteration in feed per tooth. This is not good for the surface integrity of the material and the surface finish overall deteriorates. With an increase in the input parameters, the CNC machine was used up to its maximum limits due to which the power consumed was also more.

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