The Effects of Cooling Applications on Tool Life, Surface Quality, Cutting Forces and Cutting Zone Temperature in Turning of Ni-Based Inconel 625

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Research Article

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Abstract

Nickel-based super alloys are used in many fields, especially in the aviation and aerospace industries, due to their high temperature resistance. Besides these advantages, there are some machining difficulties. Some cooling methods are used to minimize the machining difficulties of these materials. For this purpose, in this study, tool life, tool wear (Vb), surface roughness (Ra), cutting forces (Fc) and cutting zone temperature (T) were investigated in turning Inconel 625 super alloys under different cooling conditions. Experiments were carried out under three different cutting conditions (Dry, minimum quantity lubrication (MQL) and Vortex cooling methods). Three feed rates (0.08, 0.1 and 0.12 mm/rev) and three cutting speeds 60, 80, 100 m/min) were used. Tool wear tests were carried out at average cutting speed and feed rate (80 m/min and 0,1 mm/rev). After the experiments, it was concluded that the cooling application affects positively in terms of tool life, cutting zone temperature and surface roughness.

1. Introduction

Super alloys are generally used in situations where high mechanical properties and strength must be maintained at operating temperatures. Therefore, super alloys are frequently used in gas generator turbine engine components and aviation engines in the industry [1]. Besides these advantages, there are some difficulties in machining of super alloys. High thermal stress, hardness and build-up of edge (BUE) are some of these difficulties. These reasons lead to the completion of the tool life in a very short time. Using coolant is a method to prolong tool life. However, environmental factors have led to reduced usege of conventional coolants. With the restriction of the use of conventional coolants, the use of cooling methods such as MQL and vortex has increased. Basically, MQL is based on spraying the minimum amount of oil at high pressure into the cutting zone. In this way, the oil penetrates the cutting zone and improves machining efficiency [2]. Therefore, such as MQL, many researchers have included the effects of cooling methods on machinability in their researches. Sarıkaya et al. investigated the effects of cooling methods in their study. In the study, Haynes 25 super alloy was used. They concluded that MQL cooling method gives better results compared to traditional cooling methods in terms of tool wear [3]. Chetan at et al. compared the effect of cryogenic cooling and Al_2O_3 nanoparticle based MQL cooling method in the machining of a nickel-based alloy. In general, they concluded that the cryogenic cooling method is the best method for machining Nimonic 90 alloy [4]. Sterle et al. investigated the effect of single channel liquid CO_2 and MQL transmission on the surface quality in the milling of Inconel 718. The usage of non-lubricated LCO_2 during machining has been found to be as the closest method to dry machining when high surface cleaning is desired after machining [5]. Paturi et al. investigated the effect of MQL on surface roughness in turning of Inconel 718. After the study, they determined that using solid lubricant-assisted MQL improved the surface quality approximately 35% [6]. Qin at al. investigated the effects of minimum quantity lubrication on tool life and surface quality in turning of titanium alloys. They concluded that the usage of MQL has a positive effect on tool life. [7].

In addition to these studies, some processes are applied to extend the tool life and to control the high temperature that occurs in machining. Su et al. used MQL with different oils for machining AISI 1050 medium carbon steel. They concluded that the usage of MQL reduced cutting force and temperature compared to dry cutting. [8]. In addition to the experimental studies, optimization and modelling studies were also found in the literature. Sarıkaya et al. used Taguchi-based grey relational analysis in the machining of Haynes 25. They have been developed mathematical models. They used these mathematical models to formulate the cutting parameters. [9]. Sarıkaya and Güllü have modeled machining parameters in CNC turning under MQL cutting condition with Taguchi optimization. They achieved good results after processing with MQL at 120 mL / hr flow rate and 200 m / min cutting speed. [10]. Çakır et al. examined the surface quality of AA7075 and AA2024 alloys with MQL cooling technique and performed ANOVA analysis. After the experiments, they found that the increased flow rate decreased the surface roughness values and had a positive effect on the surface quality [11]. With the developing technology, the concept of nano cutting fluids and eco-friendly machining became more concerned in literature. Sarkar has made a study on the convective heat transfer correlations of nanofluids. [12]. Sohel et al. were experimentally investigated the heat transfer enhancement of a mini channel heat sink by using Al_2O_3-H_2O nanofluid [13]. Xia et al. examined the properties of convective heat transfer in microchannel heat sinks by using Al_2O_3 and TiO_2 nanofluids. They reached, indicated that the thermal conductivity and dynamic viscosity of nanofluids increased by increasing the volume fraction and TiO_2 nanofluids have a better behaviour on thermal conductivity [14]. Gong et al. investigated the effect of graphene nanofluid-based MQL on in turning of Inconel 718. They stated that the surface quality increased with increasing graphene rate [15]. Singh et al. investigated the Eco-Friendly processing of Inconel 625 under NMQL. At the end of the study, they concluded that using NMQL affected the tool life positively [16]. Gupta et al. investigated the effects of using nanoparticle-assisted MQL in titanium alloy turning. They indicated that the experimental observations and the model made a good agreement. The adaptive neuro-fuzzy inference system (ANFIS) outperformed the response surface methodology (RSM) [17]. One of the most important factors in machining of super alloys is the cutting tool. The high cost of cutting tools led the workers to achieve the optimum tool life with the right cutting parameters. Khatri and Jahan investigated tool wear mechanisms in machining of Ti-6Al-4V under flood coolant, dry and MQL conditions. They have reached that the abrasion wear is the dominant type of wear in all three methods [18]. Chetan et al. researched tool wear experimentally in turning of Nimonic 90 and Ti6Al4V super alloys under dry and MQL conditions. They concluded that MQL was better in terms of tool wear. [19]. Dhananchezian and Rajkumar, performed a comparative study of the abrasion and roughness quality during machining of Hastelloy C-276 and Nimonic 90 with carbide inserts. They concluded that, the wear rate of PVD-TiAlN coated cutting inserts was higher while turning Nimonic 90 alloy over Hastelloy C-276 after a cutting length of 50 mm and 100 mm, but after about 200 mm machining length the tool wear was high in case of Hastelloy C-276 [20]. Khalil et al. investigated the effects of cutting speed, feed rate and depth of cutting on tool wear and cutting force in turning of Nickel Titanium Shape Memory Alloy ASTM F2063. NMQL was used in the study. They concluded that the addition of Al_2O_3 nanoparticles to the base oil improved its lubricating properties and therefore it created a protective layer on the surface of the workpiece, resulting in low wear. [21]. Alagan et al. examined the effect of high pressure cooling on wear mechanisms and machining conditions in turning of Inconel 718. They have seen that with a reduction in cutting speed, adhesion and tool wear were common wear mechanisms, however, no cracks and cutting edge deterioration [22]. The control of occurred temperature during cutting is important, especially for tool life. For this reason, the previous studies aimed to find the best cutting parameters by measuring the cutting temperatures occurring during processing. [23]. Dhar et al. investigated the influence of MQL on cutting zone temperature, dimensional accuracy and chip formation in machining AISI-1040 steel. After the experiments, they determined the chip–tool interaction and chip formation gives better result under MQL condition [24].

Although the studies done with minimum quantity lubrication are quite much, on the contrary, the method of cooling with compressed air is not very common. [25, 26]. The aim of this study is to investigate, the effects of MQL and vortex on tool life, surface quality, cutting force and cutting zone temperature in turning of Ni-based Inconel 625 by taking the dry cutting conditions as reference.

2. Material And Experimental Procedure

Three different cutting conditions (Dry, MQL and Vortex) were used in the experiments. SKF LubriLeanBasic model is used for MQL. LubriOil oil, a suitable cutting oil, was used for machining Inconel as a coolant. The MQL system has a pressure of 3 bars and a flow rate of 0.9 ml/min per minute. Vortex tubes; It consists of a main tube into which high pressure air enters tangentially, which is divided into two low pressure temperature streams, hot and cold [25]. The working principle of the vortex tube is given in Fig. 1. Cooling was made using 6 bar pressure in the vortex system. The MQL nozzles are fixed at 8 mm from the insert and the vortex nozzle is fixed at 10 mm from the insert. Experimental set-up is shown in Fig. 2.

Cutting parameters and cooling conditions were chosen from the values specified by the tool manufacturer. Preliminary experiments and literature research have also been effective in determining these values. Cutting depth was determined as 0.1 mm in all experiments. Three different cutting speeds (60, 80 and 100 m/min) and three different feed rates (0.08, 0.1 and 0.12 mm/rev) were used in the experiments. A nickel-based superalloy, Inconel 625 workpiece material was used in experiments. The hardness of Inconel 625 is 388 HB. The dimensions of the test materials are &42 x 350 mm. Chemical properties of Inconel 625 are given in Table 1.

Table 1
Chemical properties of Inconel 625 (Weight%)

Material	Ni	Cr	Fe	Mo	Nb + TA	C	Mn	Si	Ti	Al	Co
Inconel 625	58	23	5	10	4.15	0.1	0.5	0.5	0.4	0.4	1

Experiments were carried out on the Johnford TC 35 CNC lathe. Technical properties of CNC Lathe Machine are given in Table 2. CNMG 120408MP and multi-layered CVD coating comprised of TiN-MT-TiCN- Al_2O_3-TiN coating cemented carbide insert (produced by Kennametal) were used in machinability tests.

Table 2
Technical properties of CNC Lathe Machine

Technical Properties	Unit values
X axis	250 mm
Z axis	600 mm
Power	10 kW
Speed	4000 rpm
Hydraulic chuck diameter	250 mm
Precision	0.001 mm

Kistler 9257 B type dynamometer with the capacity to measure three shear force components (Fc, Ff and Fr) and Kistler Type 5070 amplifier were used in the experiments. The cutting forces measured by dynamometer were converted into numerical values by using the DynoWare program software.

The surface roughness values were measured by using Mahr Perthometer surface roughness device at a travel length of 5.6 mm. The workpiece was rotated in the machining direction to measure from three different points and the average of these three values was taken. The technical specifications of Mahr Perthometer M1 device which can be seen in Table 3.

Table 3
Technical properties of Mahr Perthometer M1 device

Model	Mahr Perthometer M1
Measuring principle	Stylus method
Traversing speed (mm/sec)	0.5
Measuring ranges	100–150
Filter	Gaussian
Traversing lengths (mm)	1.75-5.6-17.5
No. of sampling lengths	Selectable from 1 to 5

The cutting temperature occurring during the experiments was measured with RAYTEK MI3 brand infrared Measurement Device. The Temperature Measuring Device, which focused on the starting point of the chip, measured during the cutting time. Measuring range of the device is between 250^{o}C-1400^{o}C.

Tool wear and material adhesion on cutting tools are visualized by using AM413ZT Polarized Digital Microscope with/at a 50X magnification (value). Maximum flank wear (V_B) was determined as 0.2 mm. After the experiments, SEM images of the cutting tools were taken (JEOL - JSM – 6060 LV). The material composition on the cutting tool was analyzed by Energy Dispersive X-ray spectroscopy (EDX).

Grey Relational Analysis (GRA)

In this study, Taguchi based GRA was used to determine optimum cutting parameters in terms of cutting force, cutting zone temperature and average surface roughness values that occured in turning of Inconel 625 superalloy. In recent years, GRA has become one of the most preferred methods for multi-parameter/multiple parameter optimization [27–30].

Results And Discussion

Tool Wear

In this study, when the maximum flank wear reached 0.2 mm, it is assumed that the cutting tool had completed its life. Tool life experiments were carried out at 80 m/min cutting speed and 0.1 mm/rev feed rate. Figure 3 shows the change in tool life depending on the machining parameters and cooling conditions. In Fig. 3, the longest tool life was obtained with MQL in experiments, while the shortest tool life value obtained from dry cutting condition. It is attributed that lubrication forms a thin layer and therefore positively affects tool life. The similar results can be found in the literature [8, 31–34].

One of the most important factors for tool life is the temperature that occurs during cutting. Increased cutting temperature may cause the tool to wears faster and thus completes its life faster. The film layer formed with MQL and the decrease of the cutting temperature provided the best result in terms of tool life. Compressed air cooling also caused the cutting zone temperature to decrease. As a result, the second best tool life after MQL was obtained in experiments using with vortex.

In this study, all tools were cut four times for 1.5 minutes (6 minutes in total) with a cutting speed of 80 m/min and a feed rate of 0.1 mm/rev Tool wear according to machining time in different cutting conditions are given in Fig. 4.

In Fig. 4, initially the wear values are very close to each other, besides the best result obtained in dry condition at 1.5 minute machining time. However, with the prolonged cutting time, obvious differences have started to occur on tool wear. Increased cutting temperatures along with increasing cutting time caused the tool to wear more in dry condition. In the experiments carried out under MQL and Vortex conditions, cutting temperatures were lower than the dry cutting condition. The minimum quantity lubrication method covers the tool-chip interface with a thin oil film, reducing friction and preventing heat build-up.

To prevent or minimize tool wear, the mechanisms that caused wear needed to be analyzed. In this study, SEM images of cutting tools were taken after the experiments and EDX analyzes were performed. SEM images of cutting tools and EDX analysis results are given in Figs. 5–7.

One of the factors affecting tool wear is Built up edge (BUE) formation. According to EDX analyzes, it is seen that alloying elements such as Ni and Cr in the composition of the workpiece material are densely encountered. BUE formation was often seen in the processing of difficult-to-cut materials such as nickel and cobalt-based superalloys. It is seen in the Figs. 5–7 where BUE formation was observed on flank side of the tool in dry condition. However, BUE formation was observed on rake in Vortex. EDX analyzes of these zones also support this situation.

Evaluation of cutting zone temperature

During machining, keeping the temperature under control has a great importance. Uncontrollable temperature plays a crucial role especially in terms of tool life. In addition to that, it significantly affects the surface quality and surface integrity. In this part of the work the effects of cutting parameters and cutting conditions on cutting zone temperature were investigated. In Fig. 8, it is seen that the highest cutting zone temperature values are reached under dry cutting condition. It is possible to say that the lowest cutting zone temperature value occurred in experiments using MQL. MQL reduces friction at the tool chip interface and also reduces cutting zone temperature values. It has been observed that the temperature values obtained with vortex are close to MQL and lower than dry conditions. It is possible to say that these results are similar to the previous studies in literature. Ji et al. compared cooling conditions (dry, MQL and flood cooling methods) and concluded that minimum quantity lubrication results lower temperature values than dry conditions [34–36]. In general, it is possible to mention that the cutting zone temperature decreases with increasing chip removal during machining. However, with the increasing feed rates and cutting speeds, the temperature values decreased contrarily to the expectation. A large amount of the heat that occur occured during machining is removed by chip. This rate can reach up to 80% under ideal conditions. But in some cases it may decrease up to 50%. It is thought that the ideal rate here occurs at 0.12 mm/rev. and 100 m/min. In all cutting conditions, this has been the case. The highest cutting temperature occurred in dry condition at 60 m/min cutting speed and 0.08 mm/rev feed rate. The lowest cutting temperature occurred in experiments with MQL at 100 m/min cutting speed and 0.12 mm/rev feed rate.

Evaluation of surface roughness

In Fig. 9, it can be seen that the surface quality improves with increasing cutting speed. This is the case for all three cutting conditions. The best surface quality occurred in experiments with MQL, followed by vortex. Improvement in surface roughness was expected with lubrication and cooling. It is possible to say that lubrication was more effective than other conditions. The lubricant that penetrates the tool chip interface facilitates the cutting and positively affects the surface quality [37]. In addition, lower temperatures and forces in MQL and vortex compared to dry condition affected the surface quality positively. Another reason for this improvement is that the chips can be removed more easily than dry condition. The chip that cannot be removed during cutting affects the surface quality negatively. In all three cutting conditions, the lowest surface roughness value was reached at 100 m/min cutting speed and 0.08 mm/rev feed rate. Even though the lowest surface roughness value was obtained in this parameter in all three cutting conditions, there was a 30% difference between MQL and dry, and a 29% difference between Vortex and dry.

Evaluation of cutting forces

In Fig. 10, it is seen that increasing cutting speeds decrease the cutting forces. It is a known situation that the temperature in the cutting zone increases with increasing cutting speeds and therefore the cutting process becomes easier. In the section where the cutting zone temperature was evaluated, it was seen that the temperature decreased with increasing cutting speeds. But here the decrease in cutting temperature has been attributed to the higher temperature removed by the chip. The increase in cutting forces with increasing feed rates can be attributed to the increase in the amount of chip removed per unit time. As with all other outputs, the best result in terms of cutting forces was obtained in experiments with MQL. It forms a film layer with the lubricating effect of MQL. As a result, decrease in cutting forces is a situation encountered in the literature [38–39]. The lowest cutting force was obtained in the experiments using MQL at 100 m/min cutting speed and 0.08 mm/rev feed rate. Then, it was carried out in experiments using Vortex at 100 m/min cutting speed and 0.08 mm/rev feed rate. The highest cutting force occurred in dry condition at 60 m/min cutting speed and 0.12 mm/rev feed rate.

Multiple Optimization

In the second phase of this study, the cooling conditions and cutting parameters were optimized according to the results of T, Fc and Ra in turning of Inconel 625 superalloy. In studies based on experimental design and analysis, especially in different cooling conditions and cutting parameters, each result is very effective and important to a certain extent, so all results are optimized at the same time (Table 4).

For this reason, Taguchi based grey relational analysis methodology was used to improve and optimize the parameters affecting the results. In the present study, the "smaller is better" approach was applied to minimize T, Fc and Ra simultaneously in the multiple response optimization process. First, the experimental results were normalized and the S/N values of the multiple response were obtained [27–30]. The values obtained as a result of the experiments and calculations are given in Table 4. In this table, the high GRG value indicates the optimum level with the strong relationship between the experimental results and the normalized values. Also, the response table for the GRG is given in Table 5. The maximum value corresponding to each parameter in this table indicates the optimum level. From now on, the optimal parameter level can be determined using Fig. 11 and/or the response Table 5. Accordingly, the best machining parameters were determined as 100 m/min cutting speed and 0.08 mm/rev feed rate in MQL cooling.

Table 4
Results of grey relational analysis

Exp no	Experiment results			Normalized values			Coefficients					
	Fc	T	Ra	Fc	T	Ra	Fc	T	Ra	GRG	S/N	Order
1	351	491	1.064	0.537	0.000	0.891	0.519	0.333	0.821	1.674	-4.47639	15
2	397	458	1.453	0.224	0.185	0.803	0.392	0.380	0.718	1.490	-3.46442	21
3	430	360	4.383	0.000	0.736	0.141	0.333	0.654	0.368	1.356	-2.64314	24
4	321	472	0.756	0.741	0.107	0.961	0.659	0.359	0.928	1.946	-5.78246	10
5	360	438	0.844	0.476	0.298	0.941	0.488	0.416	0.895	1.799	-5.10098	14
6	411	361	0.921	0.129	0.730	0.924	0.365	0.650	0.868	1.882	-5.49323	12
7	295	462	0.763	0.918	0.163	0.959	0.860	0.374	0.925	2.159	-6.68345	7
8	350	377	0.796	0.544	0.640	0.952	0.523	0.582	0.912	2.017	-6.09461	8
9	402	351	0.980	0.190	0.787	0.910	0.382	0.701	0.848	1.931	-5.71357	11
10	324	478	0.634	0.721	0.073	0.989	0.642	0.350	0.978	1.970	-5.88961	9
11	354	405	0.928	0.517	0.483	0.922	0.509	0.492	0.865	1.866	-5.41663	13
12	395	391	1.432	0.238	0.562	0.808	0.396	0.533	0.723	1.652	-4.35948	16
13	313	416	4.580	0.796	0.421	0.097	0.710	0.464	0.356	1.530	-3.69363	20
14	345	377	4.650	0.578	0.640	0.081	0.542	0.582	0.352	1.476	-3.38443	22
15	371	340	5.007	0.401	0.848	0.000	0.455	0.767	0.333	1.556	-3.83842	18
16	283	392	0.584	1.000	0.556	1.000	1.000	0.530	1.000	2.530	-8.06159	1
17	328	356	0.656	0.694	0.758	0.984	0.620	0.674	0.968	2.263	-7.09249	5
18	371	313	0.690	0.401	1.000	0.976	0.455	1.000	0.954	2.409	-7.63809	2
19	340	482	3.788	0.612	0.051	0.276	0.563	0.345	0.408	1.317	-2.38879	25
20	380	411	4.245	0.340	0.449	0.172	0.431	0.476	0.377	1.284	-2.16888	27
21	413	375	4.737	0.116	0.652	0.061	0.361	0.589	0.347	1.298	-2.26599	26
22	315	425	3.444	0.782	0.371	0.353	0.697	0.443	0.436	1.576	-3.94860	17
23	350	407	4.229	0.544	0.472	0.176	0.523	0.486	0.378	1.387	-2.84215	23
24	400	338	4.309	0.204	0.860	0.158	0.386	0.781	0.373	1.539	-3.74528	19
25	292	420	0.591	0.939	0.399	0.998	0.891	0.454	0.997	2.342	-7.39113	3
26	324	356	0.688	0.721	0.758	0.976	0.642	0.674	0.955	2.271	-7.12532	4
27	377	326	0.840	0.361	0.927	0.942	0.439	0.873	0.896	2.208	-6.87849	6

Table 5
Response table for the GRG

Parameters	Level 1	Level 2	Level 3	Delta
Cooling conditions	1.806	1.917	1.691	0.226
Cutting speed	1.545	1.632	2.237	0.691
Feed rate	1.894	1.761	1.759	0.135
Total average value of the GRG = 2.015				

Verification of Optimization

The last step in Taguchi based grey relational analysis is the verification of the optimum parameter determined. Verification experiments were performed three times using the determined optimum parameters and the results are given in Table 6.

Table 6
Results of the confirmation test

Initial parameters		Optimum parameters	
		Prediction	Experiment
Level	A1-B2-C2	A2-B3-C1	A2-B3-C1
T (°C)	416		396
Fc (N)	350		292
Ra (μm)	0.8437		0.5837
GRG	1.872	2.3971	2.396
The improvement in GRG = 0.524			
The percentage improvement in GRG = 21.87%			

When the results are evaluated, it is seen that the estimated results are better. It was found that there is a good correlation between the predicted GRG and the experimental results. The improvement in GRG from the initial parameters to the optimum parameters was 0.524 so 21.87%. The values obtained from the validation test showed that the GRG values were compatible with the confidence interval limits. As a result, Taguchi based grey relational analysis methodology for Fc, T and Ra has been successfully applied.

Conclusions

In this study, the effects of cooling conditions and cutting parameters on cutting zone temperature, surface roughness, cutting forces and tool wear in turning Nickel-based Inconel 625 material were investigated and the results are summarized below.

- It was observed that the least tool wear was obtained in the experiments with MQL.
- The longest tool life occurred at MQL, while the shortest tool life occurred in tests conducted under dry conditions.
- It has been determined that MQL application gives the best result in terms of cutting zone temperature.

- The lowest cutting force value (283 N) was obtained with MQL, followed by vortex (292 N) and dry cutting condition (295), respectively.
- While the lowest average Ra value obtained with MQL was 0.584 µm, the lowest Ra value was obtained as 0.591 µm in vortex condition and 0.763 µm in dry condition. Under all cutting conditions, the lowest average Ra value occurred at 100 m / min cutting speed and 0.08 mm / rev feed rate.
- The multiresponse optimization for the machinability characteristics namely cutting temperature, cutting force and surface roughness has been performed by applying the GRA procedures. Consequenlty, the optimal parameter for minimizing the machinability characteristics was obtained as MQL cooling, 100 m/min cutting speed and 0.08 mm/rev feed rate.

Declarations

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Ethics approval: Not applicable

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Figures

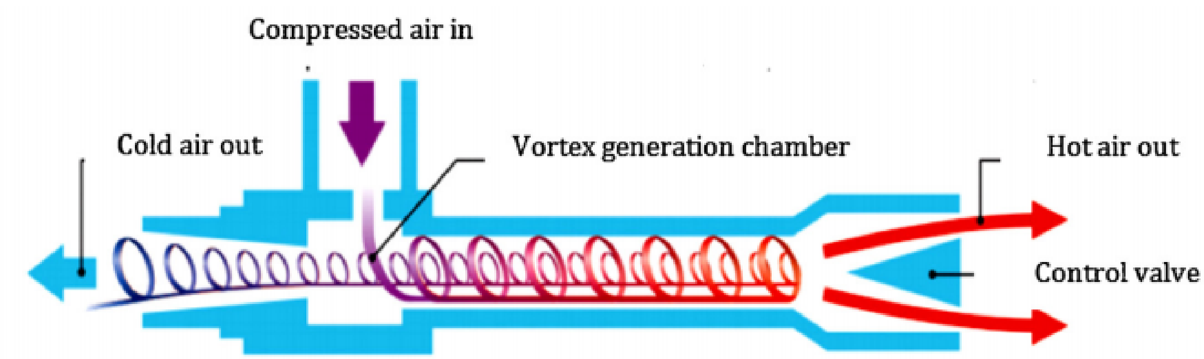

Figure 1

Vortex tube air flow [25]

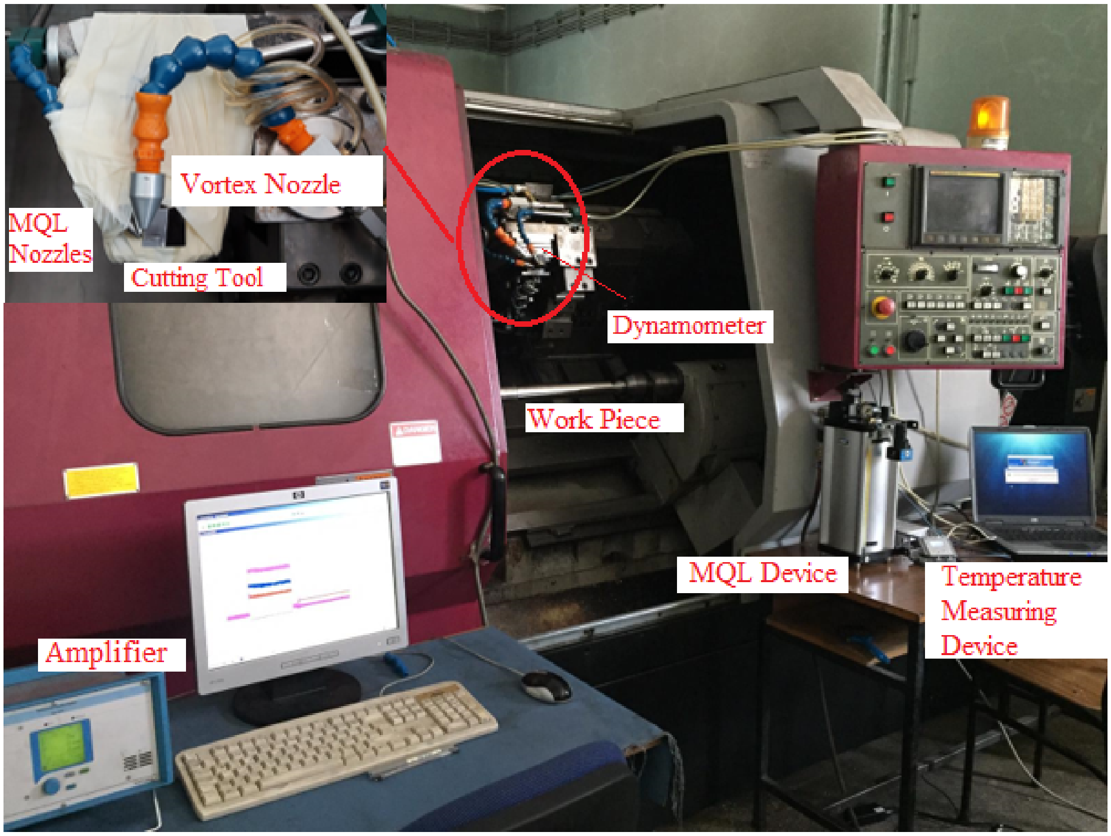

Figure 2

Experimental setup

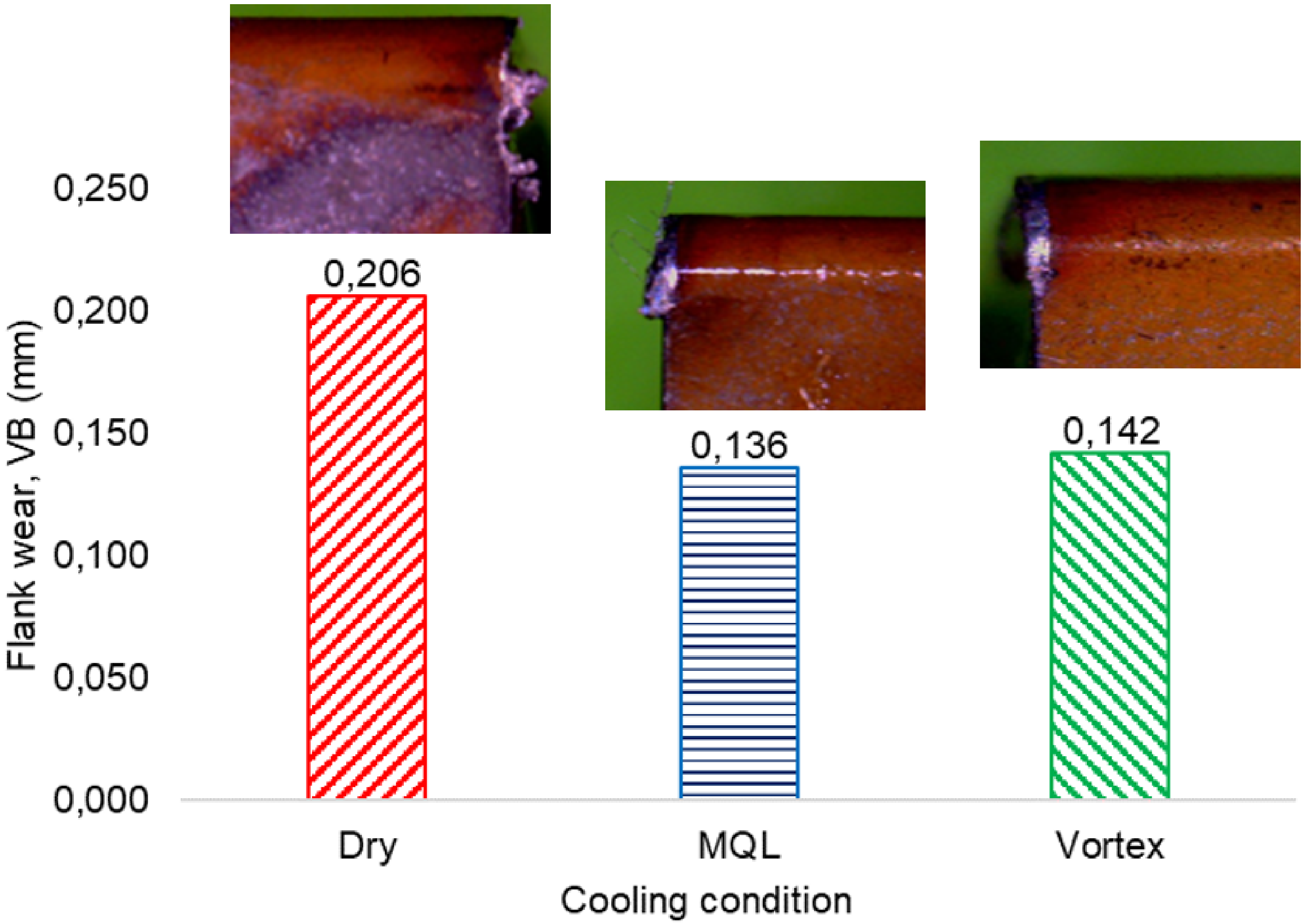

Figure 3

Change of flank wear depending on cooling conditions.

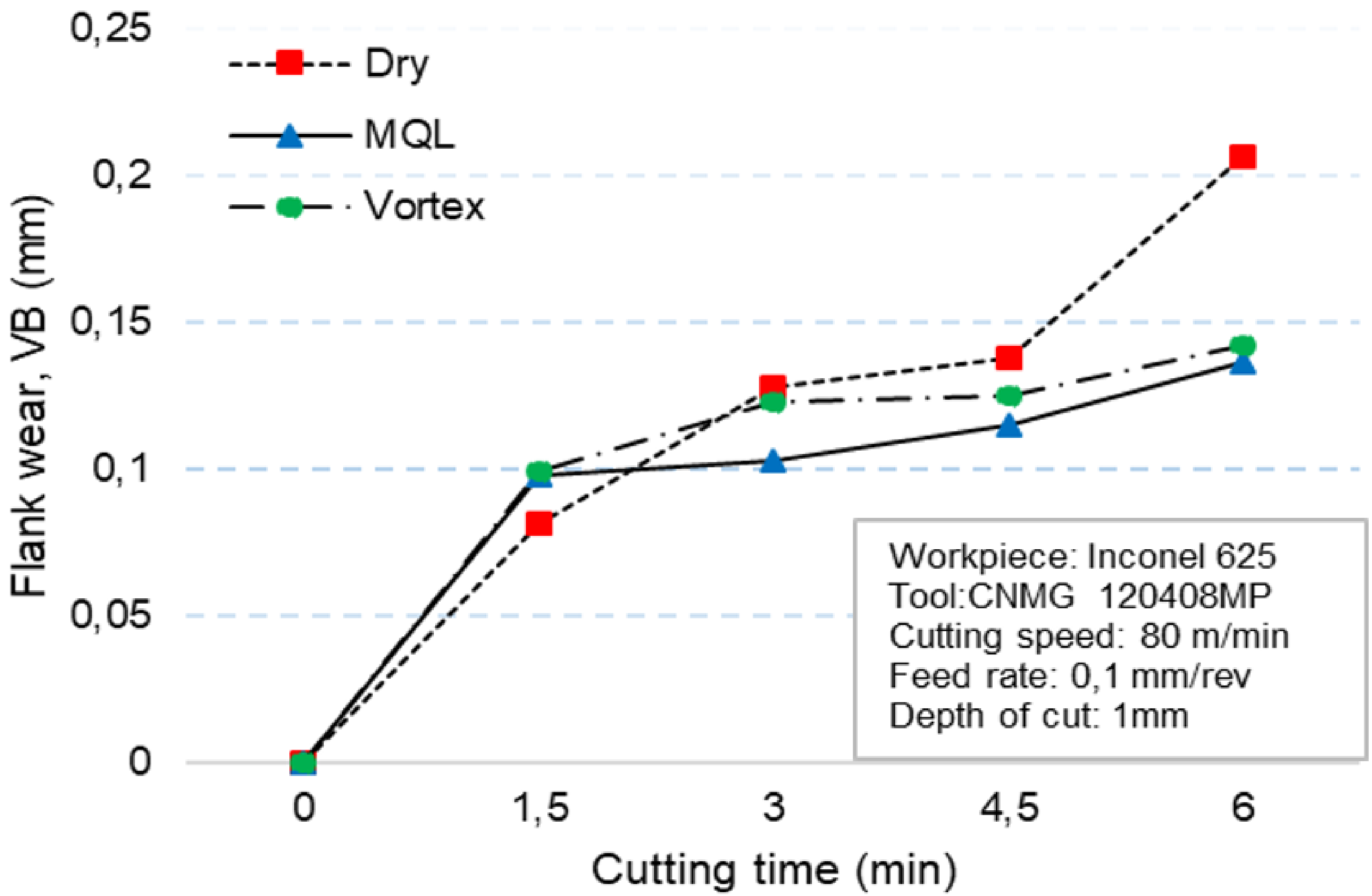

Figure 4

The relationship between cutting time and flank wear.

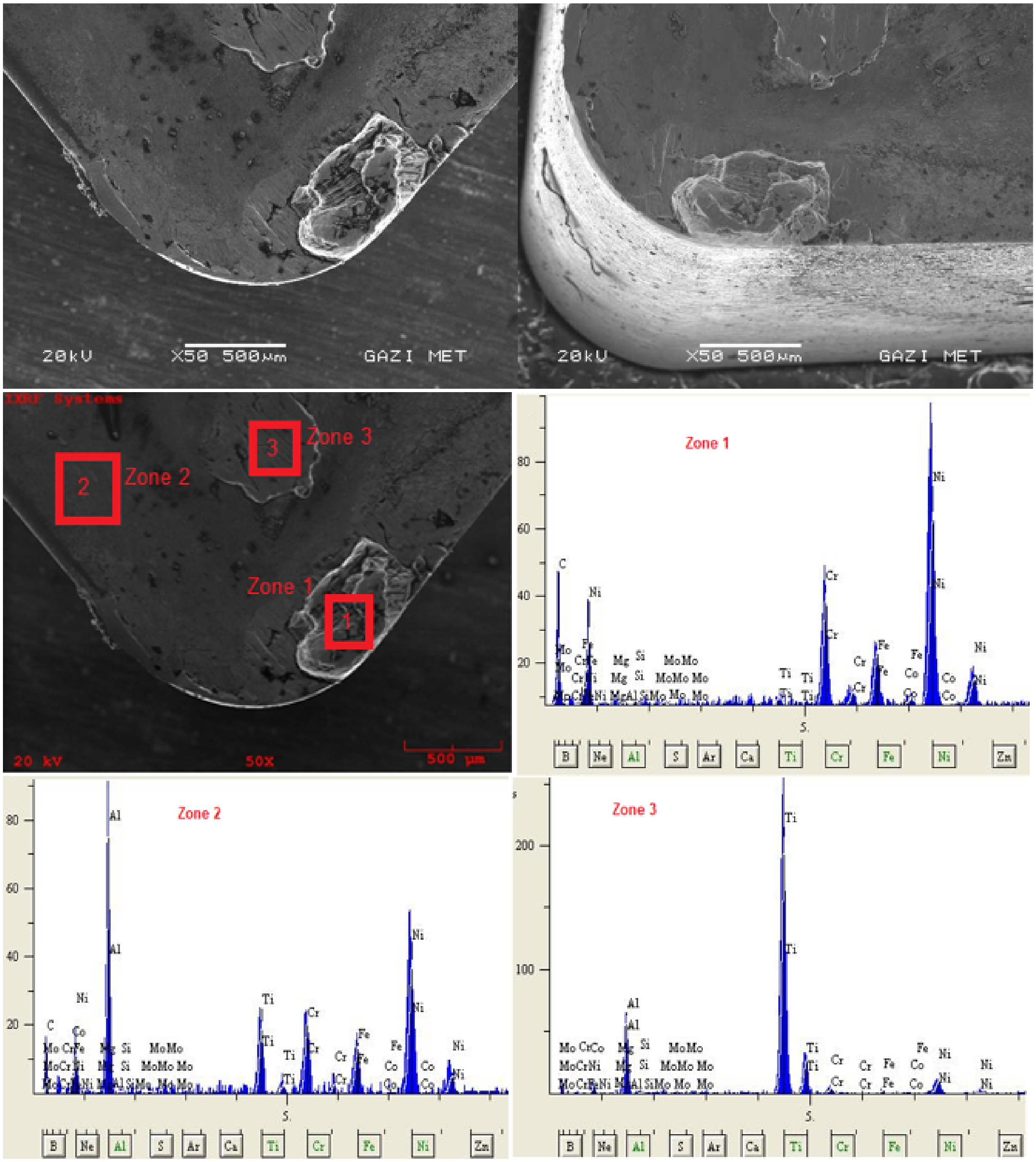

Figure 5

SEM images and EDX analysis for dry cutting condition

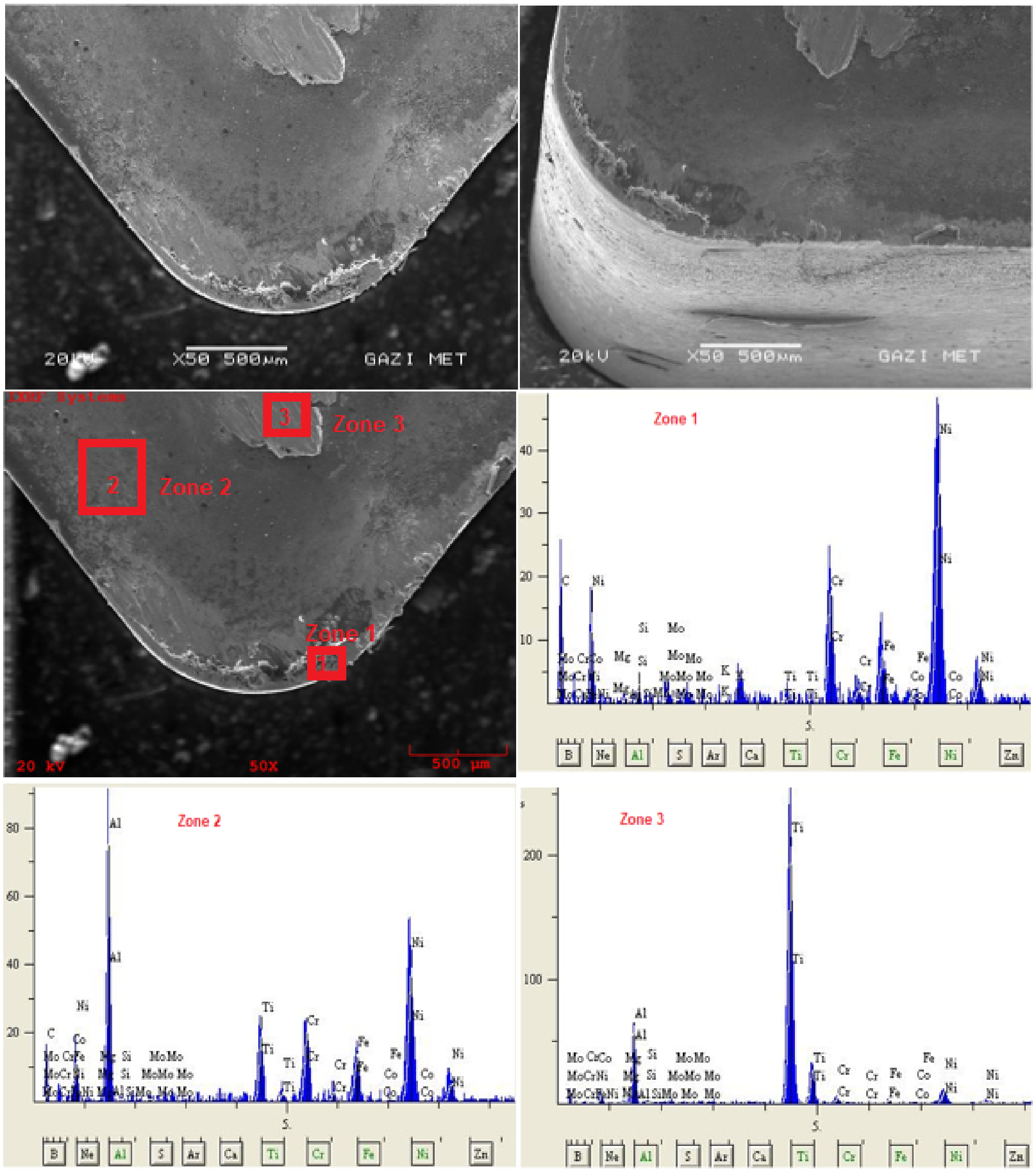

Figure 6

SEM images and EDX analysis for MQL cutting condition

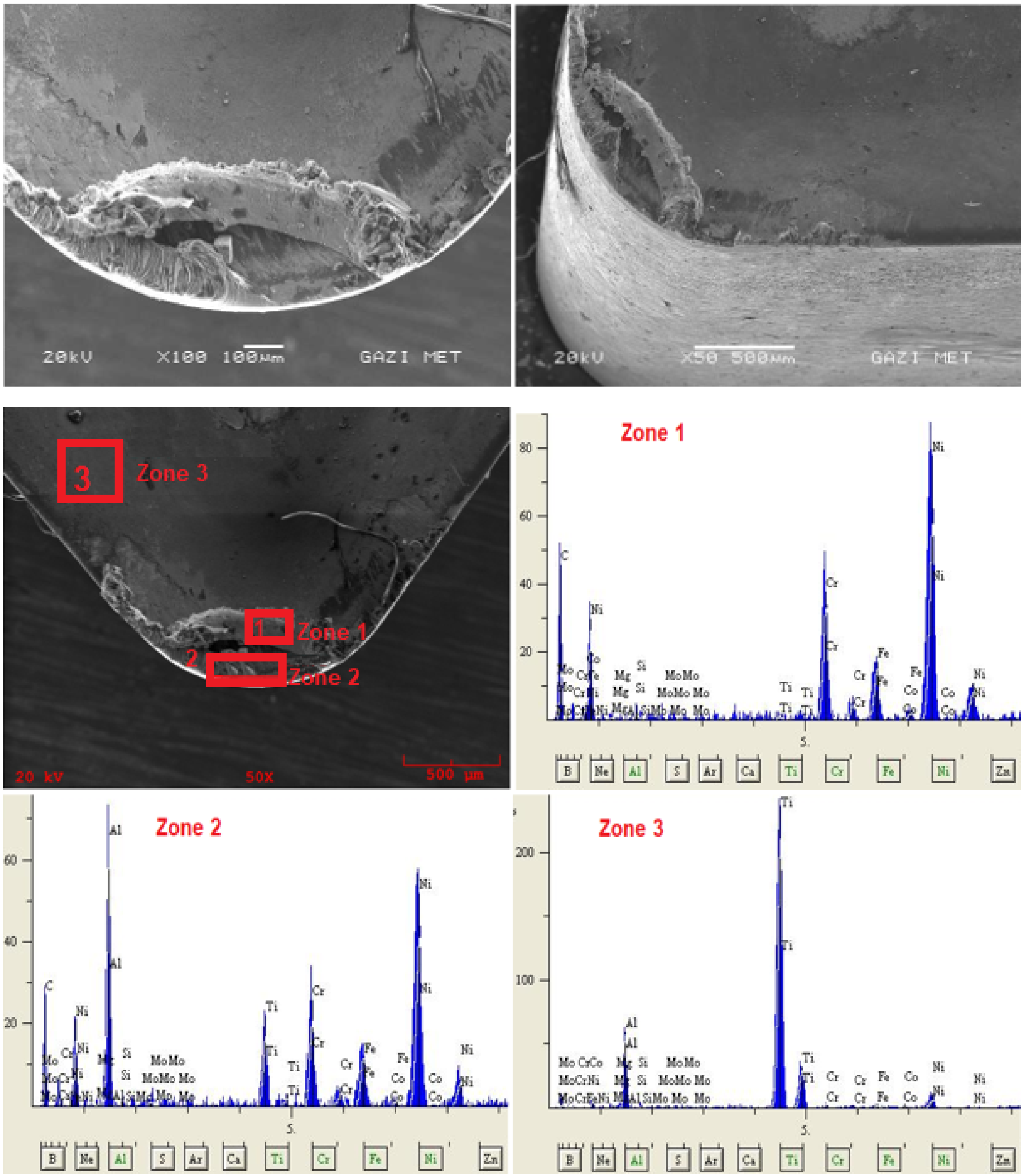

Figure 7

SEM images and EDX analysis for vortex cutting condition

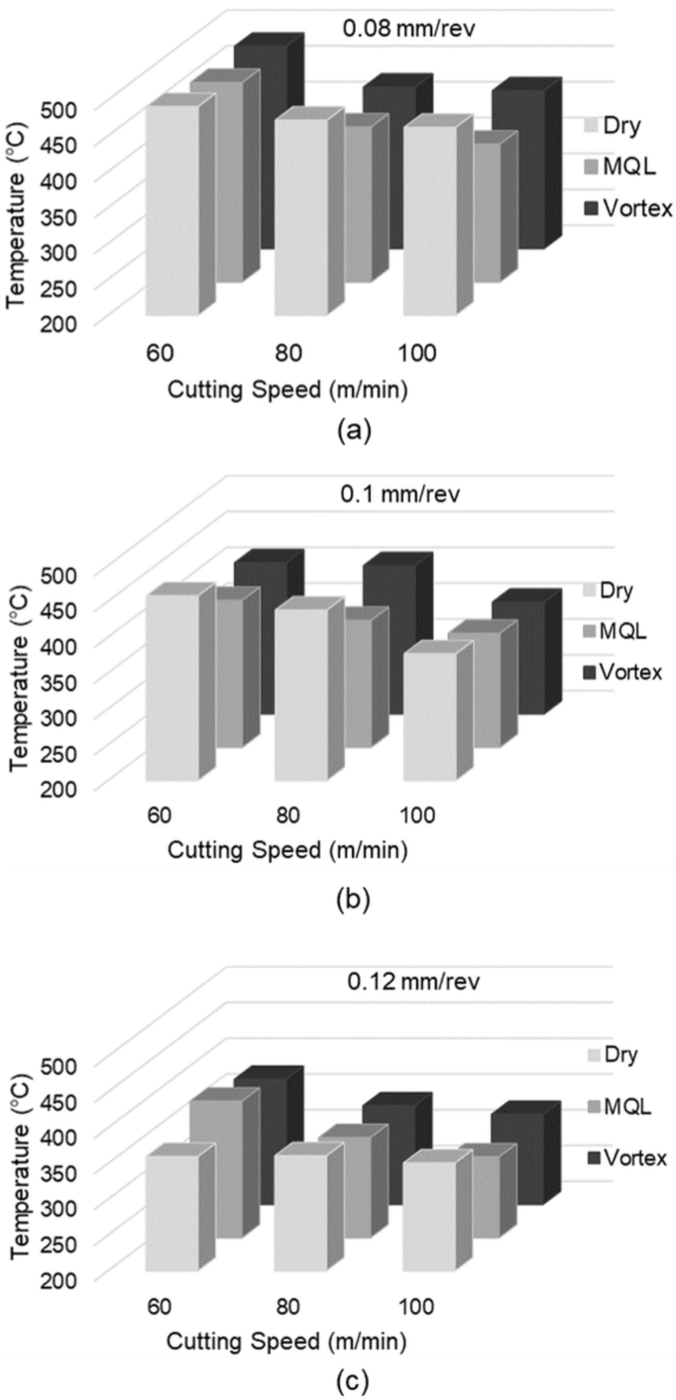

Figure 8

Change of cutting zone temperature depending on cooling conditions and cutting parameters, a) 0.08 mm/rev, b) 0.1 mm/rev c) 0.12 mm/rev

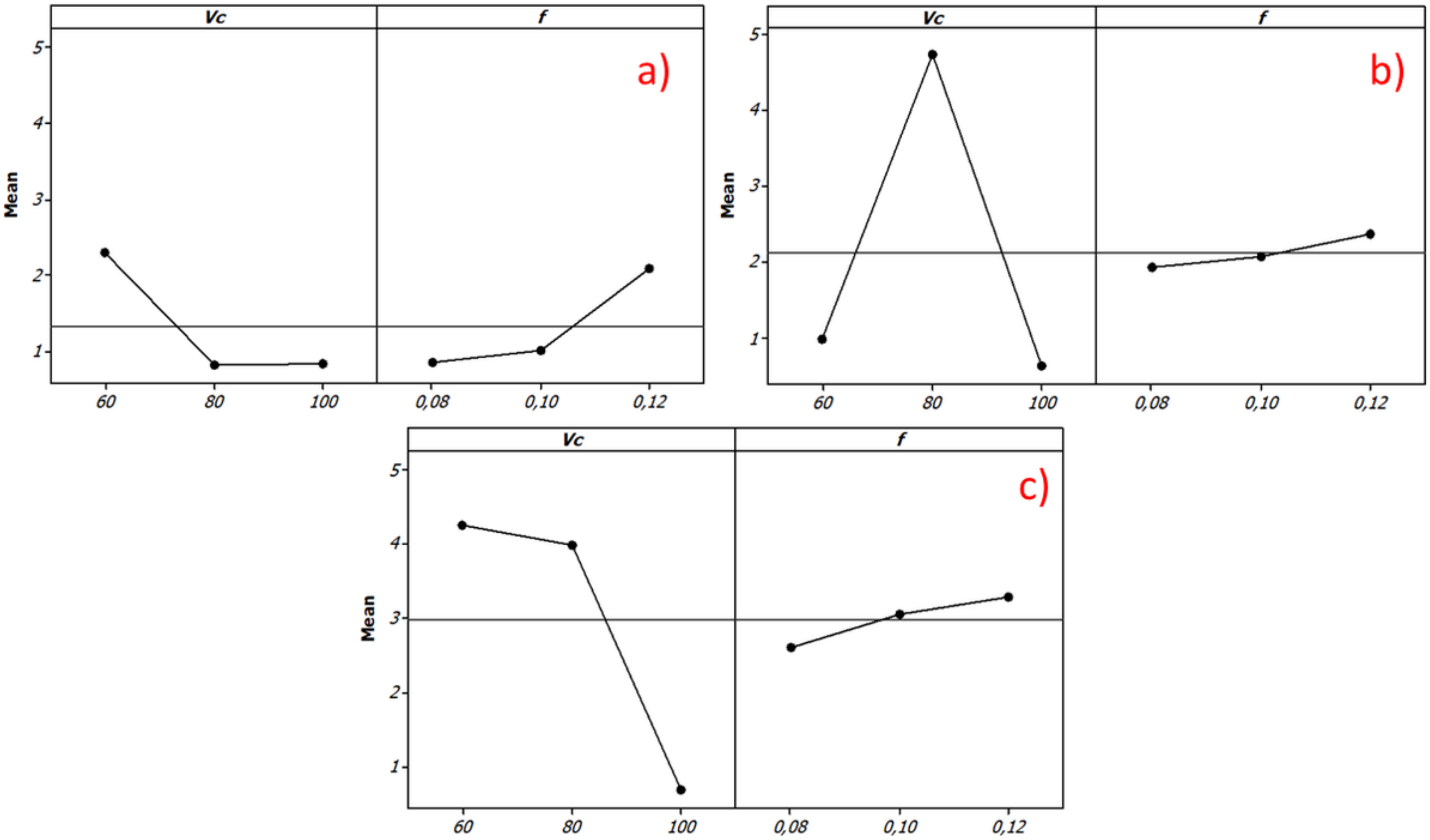

Figure 9

Change of surface roughness depending on cooling conditions and cutting parameters a) Dry b) MQL c) Vortex

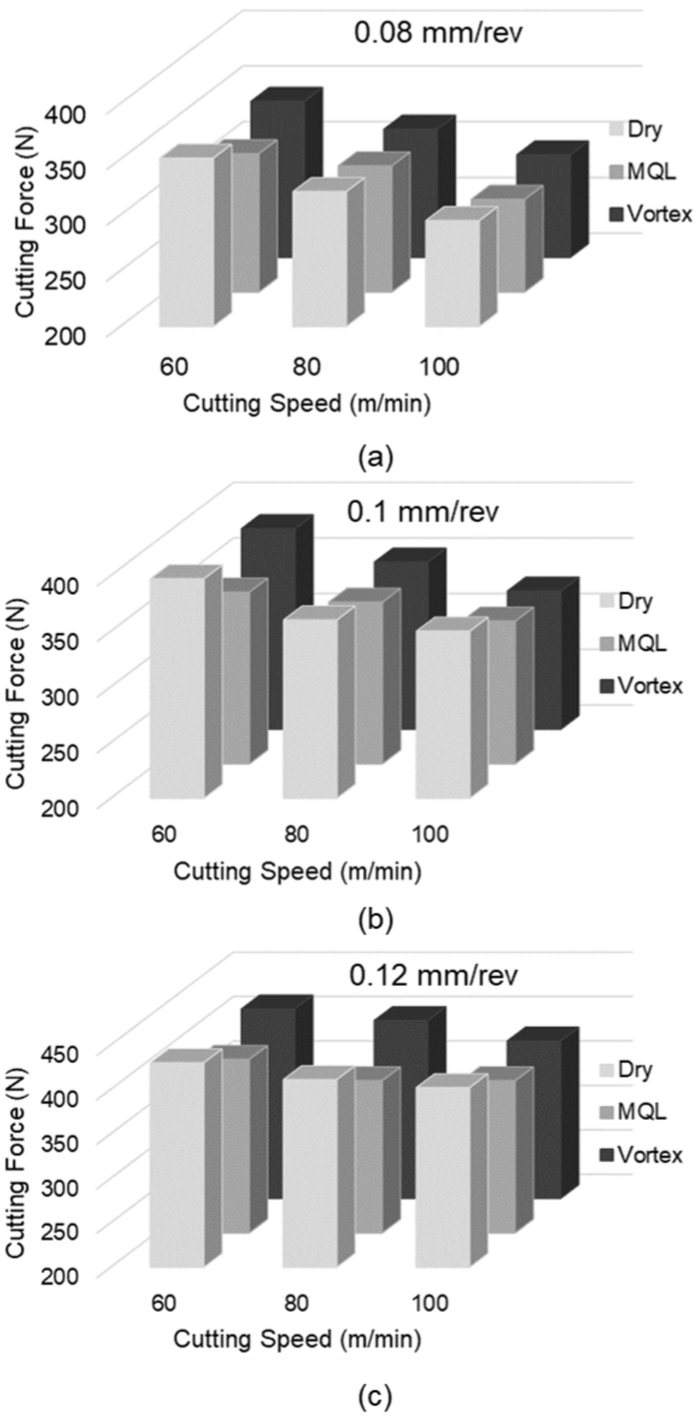

Figure 10

Change of cutting forces depending on cooling conditions and cutting parameters, a) 0.08 mm/rev, b) 0.1 mm/rev c) 0.12 mm/rev

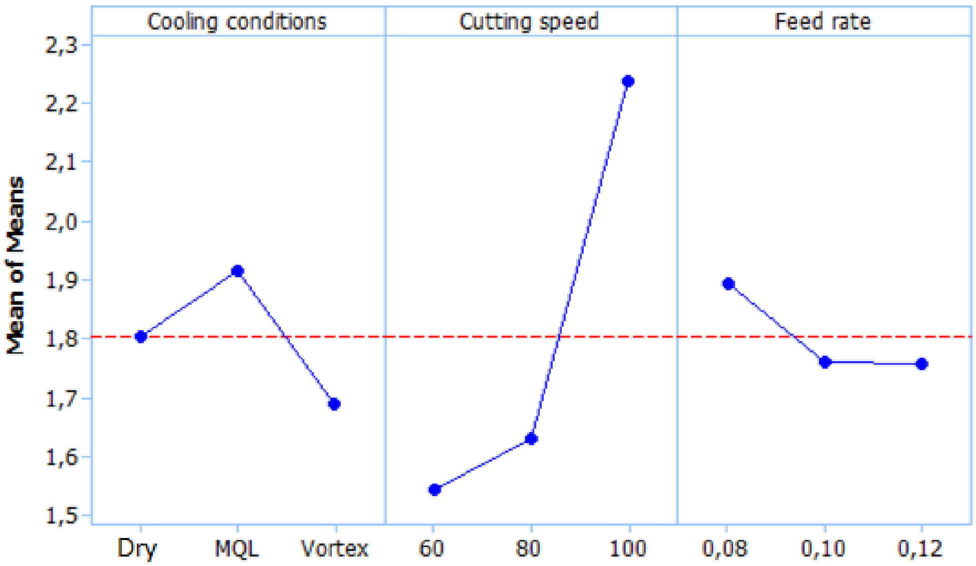

Figure 11

S/N ratios graphics for the GRG