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Sustainable Machining: MQL Technique Combined with the Vortex Tube Cooling When Turning Martensitic Stainless Steel X20Cr13

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Abstract: For the purpose of contributing to sustainable machining, the aim was to investigate the turning of martensitic stainless steel X20Cr13 under alternative cooling and lubrication techniques. The minimum quantity lubrication technique in combination with the vortex tube cooling, as the determined optimal cooling method using the Taguchi-based entropy weighted grey relational analysis (compared to emulsion and minimum quantity lubrication technique) in previous research when turning martensitic stainless steel X20Cr13, were applied in this research in accordance with the Box–Behnken design. The aim is to investigate, when applying the optimal cooling condition (minimum quantity lubrication + vortex) with the Box–Behnken design, which parameters have a significant influence on reducing the surface roughness parameters *Ra* and *Rz* and also on the tool life (*T*). The cutting speed (v_c = 260, 290 and 320 m/min), feed rate (f = 0.3, 0.35 and 0.4 mm/rev) and depth of cut (a_p = 1, 1.5 and 2 mm) were selected as cutting parameters. An exponential model for *Ra*, *Rz* and *T* was obtained. According to the ANOVA results, it can be seen that only the feed rate had a significant influence on *Ra* and *Rz*. For tool life, according to the ANOVA results, it can be seen that all three parameters (cutting speed, feed rate and depth of cut) have significant influence on the tool life (*T*). Experimental results were compared with the results of the exponential mathematical model and presented in diagrams. A new nozzle was designed for this research to allow micro-droplets from the MQL unit and chilled compressed air from the vortex tube to be connected in one stream (single-channel system) before entering the cutting zone, thus allowing for simultaneous lubrication and cooling. For the used vortex tube system with an air flow of 708 L/min and the inlet air pressure of 0.69 MPa, a temperature drop of −29 °C can be achieved in regard to the inlet air temperature of 21 °C. Therefore, the minimum quantity lubrication technique with vortex tube cooling can be recommended for turning of martensitic stainless steel X20Cr13.

Keywords: martensitic stainless steel X20Cr13; sustainable cooling/lubrication techniques; MQL + vortex tube; surface roughness; tool life

Citation: Šterpin Valić, G.; Kostadin, T.; Cukor, G.; Fabić, M. Sustainable Machining: MQL Technique Combined with the Vortex Tube Cooling When Turning Martensitic Stainless Steel X20Cr13. *Machines* **2023**, *11*, 336. https://doi.org/10.3390/machines11030336

Academic Editors: Fuat Kara, Hargovind Soni, Uğur Köklü and Onur Özbek

Received: 7 December 2022
Revised: 13 February 2023
Accepted: 24 February 2023
Published: 1 March 2023

1. Introduction

Stainless steels are difficult-to-cut materials, so it is necessary to use coolants, rinses and lubricants during their machining in high flows. Conventional cutting fluids have been identified as a major unsustainable element of the machining process. Hence, the alternative cooling and lubrication techniques are increasingly used, which lead to the ultimate goal—dry machining. There are three basic aspects that justify the development of alternative cooling and lubrication techniques: environmental impact, health impact and cost [1]. This is the reason for leaving conventional cutting fluids in machining processes.

The research of this paper is a continuation of the Sterpin Valic et al. research [2]. Sterpin Valic et al. validated the Taguchi method of orthogonal experimental designs in combination with gray relational analysis (TEGRA) based on the entropy measurement technique proposed by Wen et al. [3] for the purpose of multi-criteria optimization when turning martensitic stainless steel X20Cr13. The article compares emulsion cooling, minimum quantity lubrication (MQL) without and with the vortex tube cooling during turning of martensitic stainless steel X20Cr13. The combination of MQL with vortex tube cooling proved to be the best cooling method.

For better understanding, the MQL + vortex tube cooling method was applied in the experimental procedure of this paper in accordance with the Box–Behnken design when turning martensitic stainless steel X20Cr13 to establish the mathematical models between the machining responses *Ra*, *Rz* and *T* and the cutting speed, feed rate and depth of cut.

A brief overview of previous research in this area and the literature sources includes the previously mentioned cooling and lubrication technique; Brinksmeier et al. investigated the mechanisms of action and properties of metalworking fluids (MWFs) and gave a complete overview of them [4]. The negative effects of conventional MWFs on the environment associated with their use, i.e., pollution of surface and underground water, air, soil and pollution of agricultural products and food, are cited by Lawal [5]. Therefore, mineral oil-based MWFs require special physical and chemical treatment before disposal [5].

Successful applications of MQL have been reported in turning (Sampaio et al. [6]), milling (Uysal et al. [7]), drilling (Meena and El Mansori [8]) and grinding (Hadad and Hadi [9]). MQL resulted in improved surface quality, better chip breaking, lower cutting force and longer tool life (Sen et al. [10], Said et al. [11]).

Singh et al. [12] found that most of the research on the applicability of MQL was carried out on hardened steels AISI 1040, 1045, 1060 and 4340, nickel–chromium alloys such as Inconel 716, 718 and 800, aluminum alloy 6061 and titanium alloy Ti–6Al–4V.

Successful applications of minimum quantity cooling lubrication (MQCL) have been reported in the turning of 90CrSi steel (Ngo et al. [13]), milling of Ti-6Al-4V (Pradeep K. et al. [14]), drilling of Ti-6Al-4V (Rashid et al. [15]) and grinding of CK45 soft steel (Saberi et al. [16]). MQCL resulted in improved machinability: a longer tool life, lower cutting forces and better machined surface roughness.

However, for stainless steel turning, only a few relevant studies can be found on the application of MQL/MQCL and not one on the application of the combination of MQL with a vortex tube.

Dureja et al. [17] explored the potential of the MQL technique when turning austenitic stainless steel AISI 202 using a coated carbide cutting tool. Considering the tool wear and the surface roughness, the MQL technique showed superior results compared to wet (emulsion cooling) and dry machining.

Leppert published two papers where the tool wear [18] and surface roughness [19] when turning austenitic stainless steel AISI 316L were investigated. The MQL technique compared with conventional emulsion cooling significantly reduced the adhesion of the workpiece material to the cutting tool surfaces. Additionally, at low feed, the MQL technique gave lower roughness (*Ra* = 1.34–1.5 µm) in comparison to dry (*Ra* = 1.5–1.82 µm) and wet (emulsion-cooling) machining (*Ra* = 1.68–2.26 µm) as well as a more uniform and less-damaged machined surface.

Elmunafi et al. [20] investigated the performance of MQL with castor oil in turning AISI 420 martensitic stainless steel hardened to 48 HRC. For cutting speeds up to 170 m/min and feeds up to 0.24 mm/rev, better results were achieved compared to dry machining in terms of the better tool life of the coated carbide cutting tool, lower roughness of the machined surface and less cutting force.

Pereira et al. [21] combined the MQL technique and cryogenic cooling with liquid nitrogen (LN2) or carbon dioxide (CO_2). They found that when turning austenitic stainless steel AISI 304, the use of CO_2 as a cryogenic has a better effect on the tool life of the cutting tool, the cutting force and the integrity of the machined surface than the LN2 coolant. Combining with the MQL technique further improved machinability regardless of the cryogenic used.

Jamaludin et al. [22] constructed an MQL system that produces an extremely cold mist by supplying cold air (−13.6 °C) and hydroscopic oil (100 mL/h). When turning AISI 316 austenitic stainless steel, the constructed system can reduce the cutting force by 60 N and significantly reduce the surface roughness in contrast to dry machining.

Liu et al. [23] investigated the performance of machining austenite stainless steel AISI 304 under MQCL using air cooler and flood cutting conditions. The aim was to evaluate the surface quality and tool vibration. Lower values were achieved in surface roughness and vibrations occurred under MQCL conditions.

Recently, nano liquids have been used in the MQL technique. Thus, Singh et al. [24], when turning austenitic stainless steel AISI 304 with a coated carbide tool, recorded a reduction in the tool wear by 32.26% compared to dry and 9.68% compared to wet machining. Similarly, in comparison with dry and wet machining, the surface roughness decreased by 34.72% and 7.59%, respectively.

Boswell [25] claims that the vortex tube is capable of delivering a cooling effect very comparable to that of MWF. However, the literature on turning under vortex tube cooling conditions is poor. Four relevant studies are highlighted below.

Kostadin et al. [1] investigated vortex tube cooling when turning X20Cr13 martensitic stainless steel and obtained a lower surface roughness and thus better corrosion resistance compared to emulsion cooling.

Cukor et al. [26] determined a critical cutting speed of 248 m/min for the specific case of turning martensitic stainless steel X20Cr13 up to which vortex tube cooling compared to emulsion cooling can offer a significant economic benefit.

Liew et al. [27] compared the tool wear and the surface roughness during the turning of duplex stainless steel AISI 2205 under the conditions of cooling with an emulsion or a vortex tube. They found that the tool wear is less in the case of the application of the emulsion, while the roughness is less in the case of the application of the vortex tube.

Veić et al. [28] investigated the machinability of super duplex stainless steel EN 1.4410 under vortex tube cooling conditions and developed predictive models for surface roughness.

As we mentioned at the beginning of the paper, the stainless steels are difficult-to-cut materials, so a high flow of MWF should be used in their machining.

The basic functions of the MWF are to cool the cutting tool and the workpiece during machining, to lubricate the contact tool surfaces with the chip and machined surface and to wash away the resulting chips and particles caused by tool wear from the cutting zone. Low thermal conductivity workpiece materials, such as stainless steels, require higher volume flows of MWFs. An additional function is the short-term protection of the machined surface from corrosion. Specifically for stainless steels, all traces of MWFs should be removed immediately after machining to allow for the self-passivation of the machined surface [29]. Successful MWF application can often result in improved tool life by 1.2–4 times, intensified cutting parameters by 20–60%, and increased productivity by 10–50% [30].

Today, manufacturing companies are forced to leave conventional MWFs based on mineral oils and switch to more environmentally friendly, but at the same time more economical, alternative cooling and lubrication techniques.

The use of MWFs is associated with various harmful health impacts. It can enter the human body in several ways: in contact with the skin, through a cut or scrape on the skin, through the mouth and by inhalation. The most common health problems of machining workers are skin diseases [31]. Skin contact can happen when a worker handles parts and cutting tools covered with residual MWF without protective gloves. Additionally, if the machine tool does not have adequate MWF protection, it can spray on worker skin.

A number of health problems may be associated with the inhalation of MWF aerosol (mist), such as respiratory tract irritation, asthma, bronchitis and breathing problems [32]. Asthma can also be associated with high exposure to MWFs that contain various chemical elements, additives and pollutants [33]. Pre-existing asthma may worsen, and exposure over an extended time period can result in chronic bronchitis caused by inflammation of the main airways.

The use of MWFs is associated with environmental pollution because of the toxic waste generation. Observing losses such as evaporation, spraying, uncontrolled leakage and residual amounts on the workpiece and chip, it can be found that almost 30% of the total annual consumption of MWFs goes from the machining system to the environment [34].

Chip contamination makes it difficult to recycle, and workpieces often need to be cleaned before moving on to the next machining operation. Workpiece cleaning does not add value and can also add to the overall environmental load of the machining system.

There is a problem of MWF entering the external environment because it can pollute surface and underground water, cause soil pollution, and pollute agricultural products and food [35].

Disposal of waste MWFs is a special problem. According to European Commission Decision 2000/532/EC, they are classified as hazardous waste and must be disposed of safely in a way that does not endanger human health or the environment, [36,37].

It is estimated that MWF is approximately 8–16% of the total production cost [38], while the cost of it can increase to as much as 20–30% of the total cost when difficult-to-cut materials machining [39]. The cost of MWF is much higher compared to the cost of the cutting tool, which is only 4%.

The costs associated with MWF does not include merely the purchase and preparation costs, but also the costs of maintenance and disposal. The cost of disposal can be up to two to four times higher than the purchase price [40].

Due to the harmfulness of conventional MWF to the environment and human health, and the high additional costs in production, there is an awareness of sustainable metal machining, whose synonyms are environmentally friendly manufacturing or green manufacturing.

As Figure 1 shows, the basic dimensions of sustainability are ecological/planet, social/human and economic/profit with basic characteristics such as: ecological acceptability, lower production costs, minimum energy consumption, staff health, waste reduction and operational safety [41].

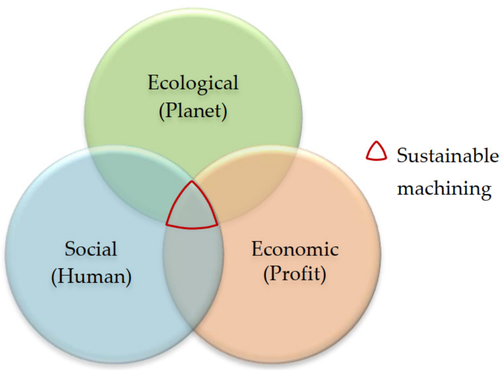

Figure 1. Sustainability dimensions.

In sustainable machining, the tool life, productivity and resource efficiency will increase, while the production cost, energy (power) required for machining and the harmful effects of MWF will decrease.

To reduce the environmental load of conventional MWFs, various approaches are being explored, from the use of biodegradable oils, through to the use of MQL/MQCL and cryogenic cooling. The ultimate goal is to completely leave MWF in metal machining and switch to dry machining.

The alternative cooling and lubrication techniques used in this work when turning martensitic stainless steel X20Cr13 are discussed below.

Vortex tube cooling with cold compressed air belongs to dry machining. The application of vortex tube cooling can replace two of the three basic functions of MWF in dry machining, these basic functions being: cooling the tool, workpiece and chip and washing away the chips from the cutting zone.

A vortex tube is a mechanical device that simultaneously produces cold and hot air from compressed air. The cold air current can reach temperatures of −50 °C while the hot air current can reach 100 °C. Figure 2 shows the vortex tube scheme of the counter-current flow whose working principle is explained in [42]. Additionally, there is a parallel flow vortex tube that has no cold air outlet next to the compressed air inlet.

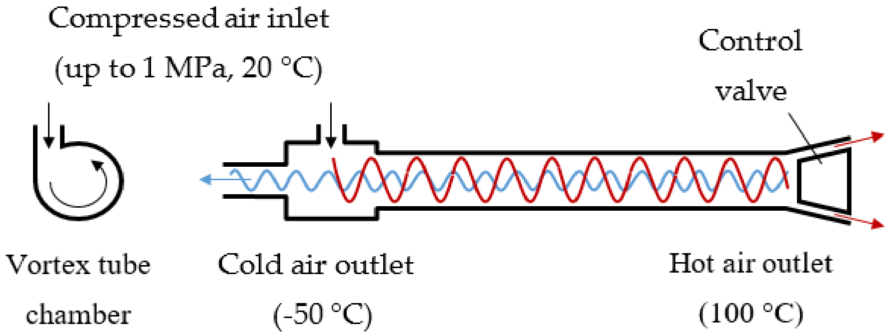

Figure 2. Counter-current flow vortex tube type.

The vortex tube cooling technique significantly reduces production costs. Additionally, most research has shown that cooled compressed air cooling is one of the most effective alternative cooling techniques in metal machining, and it is considered as the cleanest or most environmentally and healthily acceptable cooling technique. Cooling evaporation without atmospheric pollution, clean chip and the absence of harmful effects on human health are some of the positive characteristics of cooled compressed air [42].

Due to its simplicity, low weight and low investment costs, the vortex tube has a high applicability for cooling. Additionally, there are no moving parts, so the vortex tube does not burst or wear out, making maintenance easier.

The MQL/MQCL technique, also known as near-dry machining, delivers a very small amount (consumption in ml/h) of MWF aerosol to the cutting zone instead of using conventional circulating flooding systems in metal machining, so it attracts a lot of attention from researchers.

Biodegradability is the main reason for choosing vegetable oil as the basic MWF when applying the MQL technique. However, if environmental awareness was not taken into consideration, the manufacturing industry would not leave conventional MWF because of the high input cost of vegetable oil [43].

The cooling effect of MQL is negligible as it is achieved by evaporating micro-droplets of oil. So, to increase the cooling effect, advanced variants of MQL are used, which include MQCL that use cold air below 0 °C to form an aerosol or to mix with the aerosol. One such system is the MQL technique in combination with the previously described vortex tube cooling, which is applied in this article, when turning martensitic stainless steel X20Cr13.

The MQL technique significantly reduces the negative impact on the environment by reducing the consumption of MWF and eliminating the need for treatment and disposal of it. Reduced consumption also reduces the danger to workers' health at their workplaces caused by emissions of MWFs in the inhaled air and on workers' skin. MWF does not overflow or spray around the machine tool, which contributes to less pollution of the workplace and the immediate environment. The resulting chips are clean so it can be easily recycled.

MQL oil droplets should be small enough to enter the cutting zone, but larger than 5 to 10 μm so as not to lag in the air and pose a health risk to the worker [44]. Additionally, an air compressor is needed to operate the MQL system.

In general, the MQL technique uses two different delivering methods of aerosol into the cutting zone: external and internal. The aerosol consists of a gaseous (air) and a liquid (oil) phase. In the external delivering method, the aerosol is sprayed from the outside by nozzles into the cutting zone. In the internal delivering method, air and oil are mixed inside the nozzle and sprayed into the cutting zone by special single or double channels through the holes inside the cutting tool. The aerosol is available in critical places throughout machining via this method [44], but this method is also more expensive due to the increased cost of device technology.

Due to the already mentioned property of stainless steels (difficult-to-cut), two main problems can occur: short tool life and damaged machined surface.

In general, a well-cut material will be one that can be machined at high cutting speeds with an acceptable tool life and that will provide good quality of the machined surface with low costs.

Martensitic stainless steels were selected for testing in this paper. First of all, martensitic steels can be heat treated by quenching and tempering and thus achieve very high values of strength and hardness, compared to other stainless steels. Martensitic steels, however, have slightly lower corrosion resistance compared to other types of stainless steels. The thermal conductivity of stainless steels is very low, and of all the groups, martensitic ones have a slightly higher thermal conductivity, which has a positive effect on machinability. The combination of these features makes martensitic stainless steels the logical and best choice for the subject research.

Surface roughness of the machined surface is the set of all irregularities that shape the texture of the surface within the limits of the selected section to a size where shape and waviness errors are eliminated [45]. Roughness is the result of contact and the relative movement of the tool and the workpiece during the cutting process. The size of the roughness can affect the reduction in dynamic endurance (reduction in shape strength), increased friction and wear of friction-loaded surfaces, reduction of overlap at the clamping joint and acceleration of corrosion.

The basic parameters of roughness according to the standard EN ISO 4287:2008/A1:2010 are arithmetical mean deviation of profile R_a and mean height of roughness R_z [46]. The standard EN ISO 4287:2008/A1:2010 is mentioned in the technical specifications of the profilometer we used to measure roughness parameters *Ra* and *Rz*.

The degrees of surface roughness that can generally be achieved in turning are from N5 to N9. That means the parameter R_a is from 0.4 to 6.3 μm.

Tool wear directly affects the quality of the treated surface and the economy of machining, so it is most often used as a criterion for assessing machinability. It can be defined in two ways: as a change in the shape of the tool during cutting compared to the original shape resulting from the gradual loss of tool material or as a process of changing (reducing) the cutting properties of the tool. The tool wear criterion is the default allowable value of the wear measure on the tool (flank wear VB for example).

Tool life is the cutting time required to meet the tool wear criterion. That means the end of the cutting period after which further tool work is no longer economically justified.

So, the objective of the present paper is to determine the effectiveness of applying the ecological cooling method and MQL + vortex tube when turning martensitic stainless steel X20Cr13. This is an unresearched cooling method for turning the specified stainless steel. The aim is to establish the mathematical models between the machining responses *Ra*, *Rz* and *T* and the cutting speed, feed rate and depth of cut.

2. Experimental Part—Turning of Martensitic Stainless Steel

2.1. Material, Methods and Equipment

In the experimental procedure, martensitic stainless steel X20Cr13 was used (in a quenched and tempered condition). The MQL + vortex tube cooling method was applied in accordance with the Box–Behnken design. The plan of the experimental study and data analysis is shown in Figure 3.

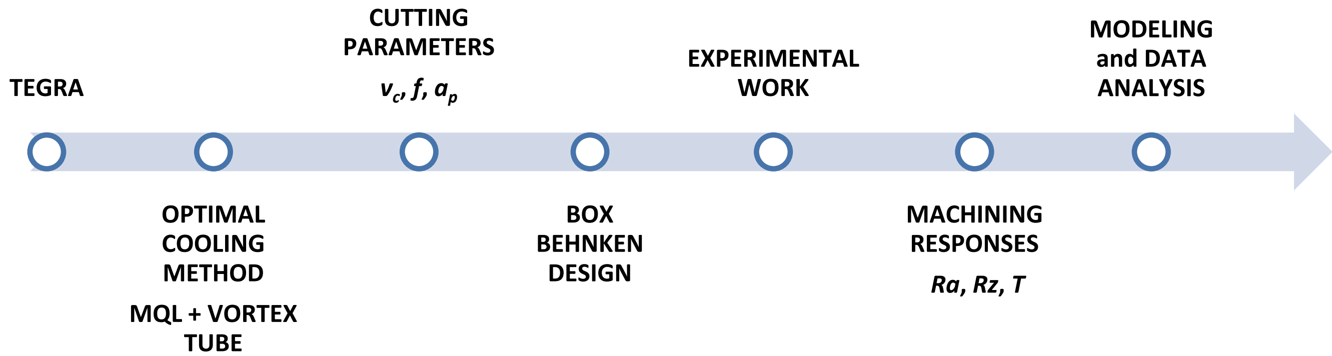

Figure 3. Plan of experimental study and data analysis.

Chemical composition and main mechanical properties are defined in Tables 1 and 2. The application of X20Cr13 is for surgical instruments and machine parts. This steel is often used as a tool steel. Tables 3 and 4 present the levels of cutting parameters and coded symbols and the Box–Behnken design (15 experiments). With a Box–Behnken design, each cutting parameter has 3 levels. The X_1 is cutting speed, v_c [m/min], X_2 is feed rate, f [mm/rev] and X_3 is depth of cut, a_p [mm]. The basis for choosing the cutting parameter levels was the tool manufacturer's recommendation (based on workpiece and tool type of material) and preliminary research on the lathe in the stated cooling conditions.

Table 1. Chemical composition of X20Cr13.

Fe, %	C, %	Si, %	Mn, %	P, %	S, %	Cr, %	Mo, %	Ni, %	V, %	Nb, %	Cu, %
85.85	0.236	0.352	0.683	0.044	0.023	11.97	0.125	0.299	0.053	0.07	0.195

Table 2. Mechanical properties of X20Cr13.

Yield Strength $R_{p0,2}$, MPa	Tensile Strength R_m, MPa	Elongation A_5, %	Contraction Z, %	Hardness HB
750	881	16.36	47	272

Table 3. Cutting parameter levels and coded symbols.

Parameter	Coded Symbols	Levels		
		−1	0	1
Cutting speed v_c, m/min	X_1	260	290	320
Feed rate f, mm/rev	X_2	0.3	0.35	0.4
Depth of cut a_p, mm	X_3	1	1.5	2

Turning was executed on the CNC lathe Prvomajska TU 360, Figure 4. Seco DNMG 150608-MF-4 cutting inserts of TM 4000 grade (tungsten carbide) and tool holder DDJNL 2525M15-M were used. The vortex tube cooling and MQL technique were performed using the Presing B7000 reciprocating compressor, the Ranque–Hilsch counter-current flow EXAIR vortex tube, model 3825, with an air flow of 708 L/min (it also contains a generator with a lower air flow of 425 L/min), inlet air pressure of 0.69 MPa and cooled air temperature of −8 °C, and the MQL external system SKF VectoLub with a VE1B biodegradable LUB 200 oil-supplied unit with the integrated tank capacity of 0.3 L (air flow at 6 bar is 170 L/min, micropump delivery rate from 7 to 30 mm^3/stroke, pump working frequency is 1 strokes/s).

Table 4. Box–Behnken design for three cutting parameters.

Experiment Number	X_1	X_2	X_3
1	−1 (260)	−1 (0.3)	0 (1.5)
2	1 (320)	−1 (0.3)	0 (1.5)
3	−1 (260)	1 (0.4)	0 (1.5)
4	1 (320)	1 (0.4)	0 (1.5)
5	−1 (260)	0 (0.35)	−1 (1)
6	1 (320)	0 (0.35)	−1 (1)
7	−1 (260)	0 (0.35)	1 (2)
8	1 (320)	0 (0.35)	1 (2)
9	0 (290)	−1 (0.3)	−1 (1)
10	0 (290)	1 (0.4)	−1 (1)
11	0 (290)	−1 (0.3)	1 (2)
12	0 (290)	1 (0.4)	1 (2)
13	0 (290)	0 (0.35)	0 (1.5)
14	0 (290)	0 (0.35)	0 (1.5)
15	0 (290)	0 (0.35)	0 (1.5)

MQL and vortex tube setup. Compressed air is coming in front of the MQL unit where are two ball valves that open/close the air flow to the MQL unit and vortex tube, Figure 4. In this way, three cooling/lubrication methods can be applied: MQL lubrication or vortex tube cooling or a combination of the MQL and vortex tube.

The SolidWorks nozzle model enables connection of MQL micro-droplets and vortex tube cooled compressed air in one stream (single-channel system) before entering the cutting zone, thus allowing for simultaneous lubrication and cooling. The SolidWorks nozzle model was printed using Formlabs 3D Form 2 printer (stereolithography principle) and standard grey photoreactive resin [2]. It is important that the nozzle is setup as close as possible to the cutting edge, with distances between 3 to 9 mm and with a nozzle angle of 45° [47,48]. The closer the nozzle is, the more amount of lubricant is delivered on the tool–chip interfaces, i.e., the total mass of oil mist particles accumulated on the tool–chip interfaces delivered by the nozzle increases. The closest nozzle distance improved the tool life [48] and reduces the cutting temperature [47]. So, a mean value of 6 mm is setup for the nozzle distance with a nozzle angle of 45° and the oil mist is directed on the tool edge. Additionally, the cutting parameters have significant influence in the turning process; the nozzle orientation has the least significance [49]. That helps us to understand the importance of cutting parameters as key success factors which can be assisted with MQL fluids and other input parameters. Input parameters, such as nozzle distance and angle, can be investigated for future research.

Diameter of the machined parts was 80 mm, and the length of turning was 463 mm.

Surface roughness was measured with a profilometer Hommel Tester T1000 manufactured by JENOPTIK, Germany, Figure 4. Surface roughness parameters were measured according to the standard EN ISO 4287:2008/A1:2010, [31]. During the experiments, the arithmetical mean deviation of the profile (R_a) and main height of roughness (Rz) were measured directly in the lathe to avoid possible errors due to the workpiece re-clamping operation. The mean value of three measurements was adopted as a result of each experiment to reduce deviation. The wear of the cutting tool was analyzed using a Dino Lite Pro digital USB microscope manufactured by AnMo Electronics Corporation, Taiwan, equipped with a camera, Figure 4. The microscope has a resolution of 1280 × 1024 pixels with a magnification of up to 200 X.

Figure 4. Experimental setup for turning process: (**a**) MQL and vortex tube setup, (**b**) SolidWorks nozzle model and original printed nozzle, (**c**) surface roughness measurement, (**d**) tool wear measurement.

2.2. Results and Discussion

Table 5 shows the surface roughness (*Ra* and *Rz*) results of the machined surface and tool life (*T*) results for the flank wear criterion *VB* = 0.3 mm during turning in the condition of MQL combined with vortex tube cooling. The aim of the paper was to obtain the degree of roughness N7 for the arithmetical mean deviation of profile (*Ra*), which is the average application in turning, and this was obtained in all experiments. As we mentioned before, martensitic stainless steels have a slightly lower corrosion resistance compared to other stainless steels. Given that lower surface roughness gives better corrosion resistance, the obtained results are satisfactory in this aspect as well.

Table 5. Experimental results.

Experiment Number	Output Responses		
	***Ra*, µm**	***Rz*, µm**	***T*, min**
1	1.556	7.97	7.5
2	1.349	7.07	2.45
3	1.774	8.85	2.81
4	1.777	8.28	1.31
5	1.606	8.18	13.7
6	1.767	8.30	3.8
7	1.582	8.09	2.87
8	1.685	8.31	1.13
9	1.415	7.54	7.486
10	1.718	8.39	8.39
11	1.490	7.82	2.19
12	1.844	10.08	1.02
13	1.685	8.28	2.83
14	1.623	8.15	2.94
15	1.651	8.21	2.91

2.2.1. Analysis of Surface Roughness

The results of multiple regression analysis (according to Microsoft Excel) are listed in Table 6 and give the following mathematical model of the arithmetical mean deviation of profile (*Ra*) for turning under MQL with the vortex tube cooling condition:

$$Ra = e^{1.118}\, {v_c}^{0.020}\, f^{0.713}\, {a_p}^{0.020} \tag{1}$$

The value of the coefficient of determination (*R Square*) in Table 6 is high, so it indicates a solid relationship, which means that the mathematical model (1) is representative.

According to the ANOVA results, it can be seen that only the feed rate has significant influence on the arithmetical mean deviation of profile *Ra* (p-value < 0.05).

Mathematical model (1) is shown graphically in Figure 5 in order to analyze the influence of the feed rate on the roughness parameter *Ra*. As the feed rate increases, the roughness parameter *Ra* increases, and it is clearly seen that the cutting depth and cutting speed have no significant influence.

Table 6. Multiple regression analysis (Excel) for a mathematical model of the *Ra*.

Regression Statistics						
Multiple R	0.883					
R Square	0.779					
Adjusted R Square	0.719					
Standard Error	0.047					
Observations	15					
ANOVA						
	df	SS	MS	F	Significance F	
Regression	3	0.085	0.028	12.959	0.00062344	
Residual	11	0.024	0.002			
Total	14	0.109				
	Coefficients	Standard Error	t Stat	*p*-value	Lower 95%	Upper 95%
Intercept	1.118	0.909	1.230	0.244	−0.882	3.118
v_c	0.020	0.159	0.128	0.901	−0.329	0.370
f	0.713	0.115	6.219	6.5×10^{-5}	0.460	0.965
a_p	0.020	0.047	0.430	0.675	−0.040	0.178

Table 7 shows a comparison of the results obtained via the experiment and the results obtained via the mathematical model. The difference between these values is called the residue, whose value should be as small as possible. The diagram in Figure 6 is a graphical representation of the difference between the results of the experiment and the results of the mathematical model.

Table 7. Experimental results, model results and residues for *Ra*.

Experiment Number	**Experiment *Ra*, µm**	**Mathematical Model *Ra*, µm**	**Residue**
1	1.556	1.461	0.095
2	1.349	1.467	−0.118
3	1.774	1.793	−0.019
4	1.777	1.801	−0.024
5	1.606	1.617	−0.011
6	1.767	1.624	0.143
7	1.582	1.640	−0.058
8	1.685	1.647	0.039
9	1.415	1.452	−0.037
10	1.718	1.783	−0.065
11	1.490	1.472	0.018
12	1.844	1.808	0.037
13	1.685	1.634	0.051
14	1.623	1.634	−0.011
15	1.651	1.634	0.017

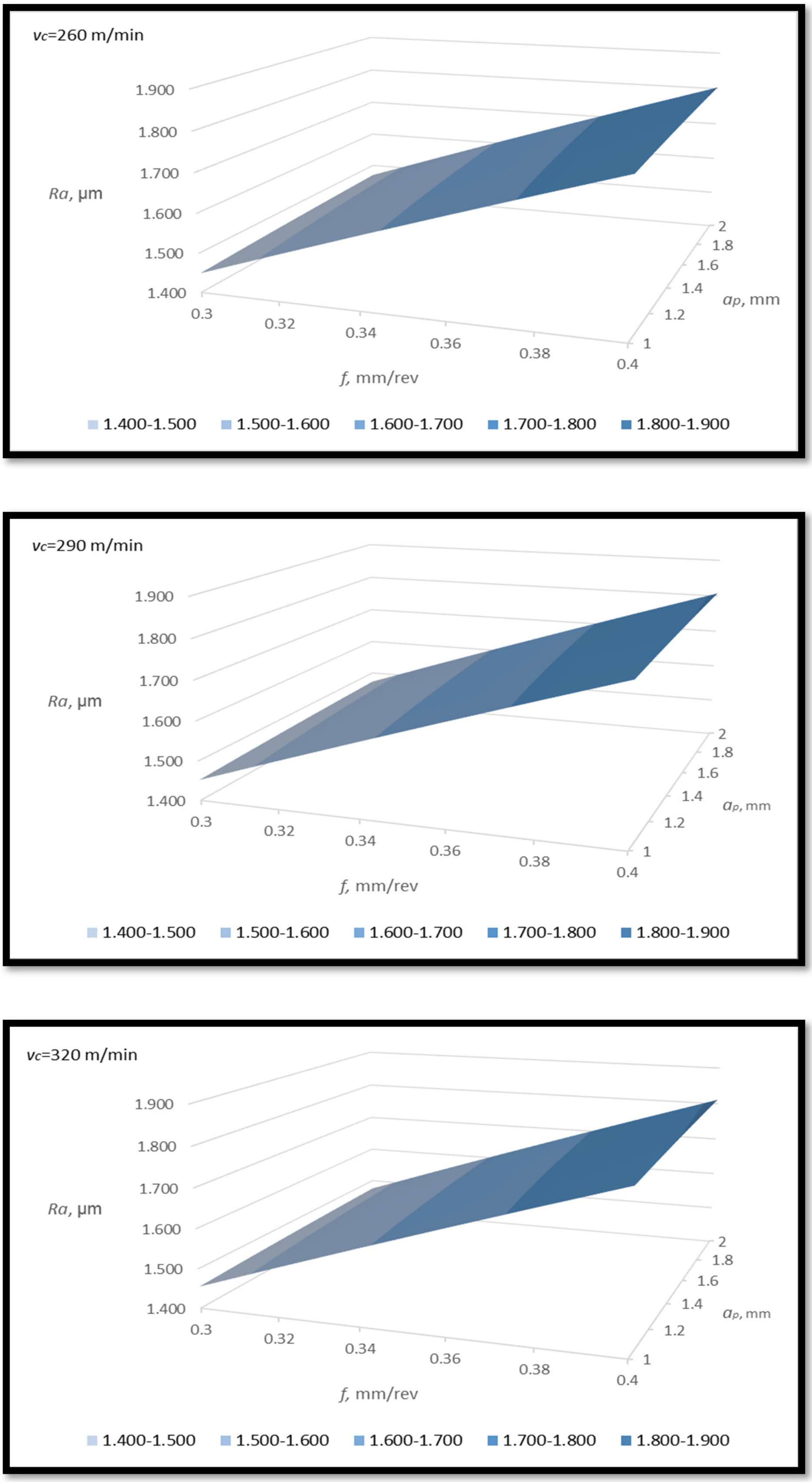

Figure 5. Achievable roughness parameter *Ra* when turning martensitic stainless steel X20Cr13 under MQL + vortex conditions for cutting speed (v_c) = 260, 290 and 320 m/min: (f) feed rate, (a_p) depth of cut.

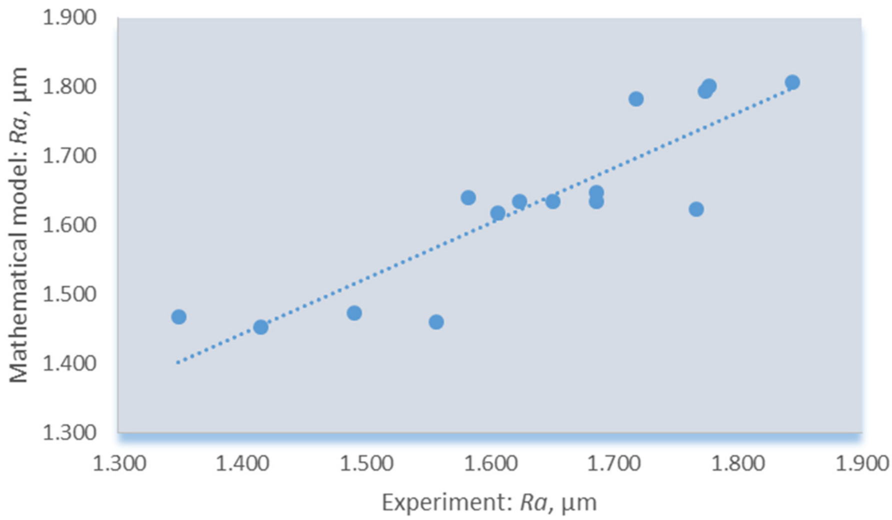

Figure 6. Experiment–mathematical model comparison diagram for *Ra*.

Analysis of the results of measuring *Rz* is calculated in the same way (Table 8).

Table 8. Multiple regression analysis (Excel) for a mathematical model of the *Rz*.

Regression Statistics						
Multiple R	0.825					
R Square	0.681					
Adjusted R Square	0.593					
Standard Error	0.049					
Observations	15					
ANOVA						
	df	SS	MS	F	Significance F	
Regression	3	0.056	0.019	7.812	0.005	
Residual	11	0.026	0.002			
Total	14	0.082				
	Coefficients	Standard Error	t Stat	*p*-value	Lower 95%	Upper 95%
Intercept	3.609	0.949	3.801	0.003	1.519	5.699
v_c	−0.169	0.166	−1.018	0.330	−0.534	0.196
f	0.541	0.120	4.522	0.001	0.278	0.805
a_p	0.069	0.049	1.397	0.190	−0.040	0.178

The results of the multiple regression analysis (according to Microsoft Excel) are listed in Table 8 and give the following mathematical model of the mean height of roughness (*Rz*) for turning under MQL with the vortex tube cooling condition:

$$Rz = e^{3.609}\, v_c^{-0.1690}\, f^{0.541}\, a_p^{0.069} \quad (2)$$

The value of the coefficient of determination (R Square) in Table 8 indicates a solid relationship, which means that the mathematical model (2) is representative.

According to the ANOVA results, it can be seen that only the feed rate has significant influence on the mean height of roughness *Rz* (*p*-value < 0.05).

Mathematical model (2) is shown graphically in Figure 7 in order to analyze the influence of the feed rate on the roughness parameter (*Rz*). As the feed rate increases, the roughness parameter (*Rz*) increases, and it is clearly seen that the cutting depth and cutting speed have no significant influence, as well as with *Ra*.

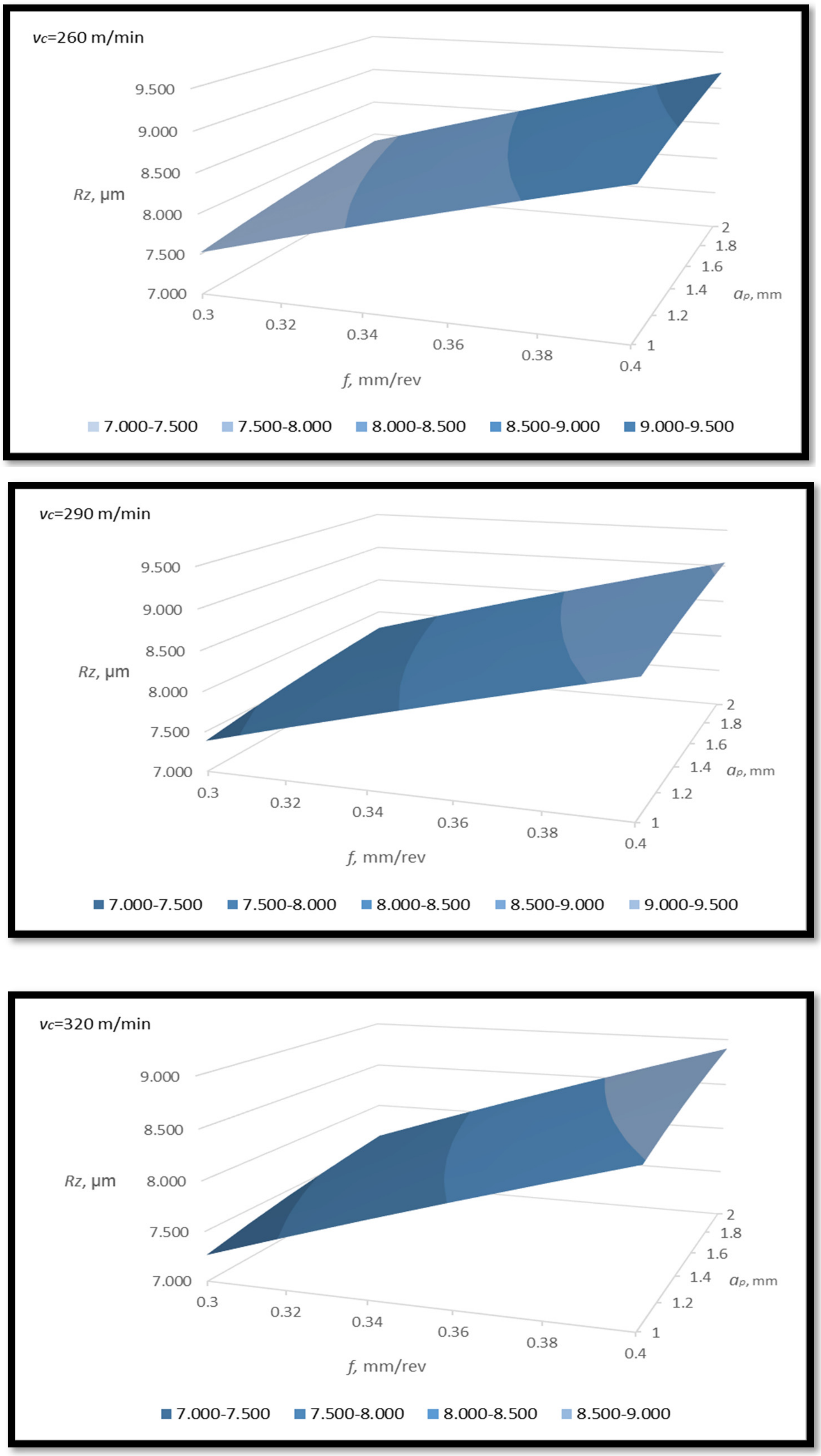

Figure 7. Achievable roughness parameter *Rz* when turning martensitic stainless steel X20Cr13 under MQL + vortex conditions for cutting speed (v_c) = 260, 290 and 320 m/min: (f) feed rate, (a_p) depth of cut.

Table 9 shows a comparison of the results obtained via the experiment and the results obtained via the mathematical model. The diagram in Figure 8 is a graphical representation of the difference between the results of the experiment and the mathematical model.

Table 9. Experiment results, model results and residues for *Rz*.

Experiment Number	Experiment *Rz*, µm	Mathematical Model *Rz*, µm	Residue
1	7.97	7.74	0.24
2	7.07	7.47	−0.40
3	8.85	9.04	−0.19
4	8.28	8.73	−0.45
5	8.18	8.18	0.00
6	8.30	7.89	0.40
7	8.09	8.58	−0.49
8	8.31	8.28	0.03
9	7.54	7.38	0.15
10	8.39	8.63	−0.23
11	7.82	7.75	0.07
12	10.08	9.05	1.03
13	8.28	8.25	0.02
14	8.15	8.25	−0.10
15	8.21	8.25	−0.04

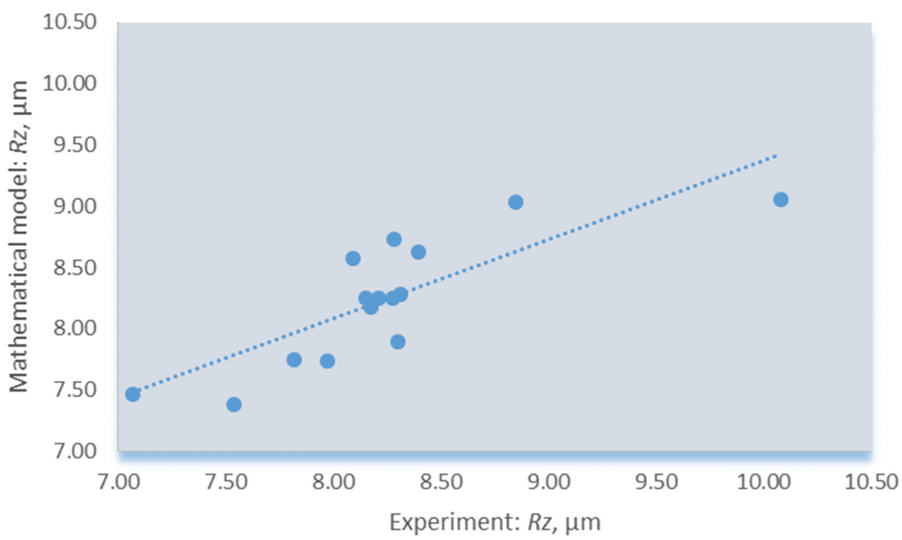

Figure 8. Experiment–mathematical model comparison diagram for *Rz*.

2.2.2. Analysis of Tool Life

The results of the multiple regression analysis (according to Microsoft Excel) are listed in Table 10 and give the following mathematical model of the tool life (T) for turning with MQL combined with vortex tube cooling:

$$T = e^{27.876} v_c^{-4.930} f^{-1.950} a_p^{-2.222} \quad (3)$$

The value of the coefficient of determination (R Square) in Table 10 is high, so it indicates a solid relationship, which means that the mathematical model (3) is representative.

Table 10. Multiple regression analysis (Excel) for a mathematical model of the *T*.

Regression Statistics						
Multiple R	0.971					
R Square	0.943					
Adjusted R Square	0.928					
Standard Error	0.203					
Observations	15					
ANOVA						
	df	SS	MS	F	Significance F	
Regression	3	7.532	2.511	60.974	3.85101×10^{-7}	
Residual	11	0.453	0.0411			
Total	14	7.985				
	Coefficients	Standard Error	t Stat	*p*-value	Lower 95%	Upper 95%
Intercept	27.876	3.950	7.058	2.10546×10^{-5}	19.183	36.570
v_c	−4.930	0.691	−7.139	1.89581×10^{-5}	−6.450	−3.410
f	−1.950	0.498	−3.914	0.002415885	−3.046	−0.854
a_p	−2.222	0.206	−10.804	3.39625×10^{-7}	−2.674	−1.769

According to the ANOVA results, it can be seen that the cutting speed, feed rate and depth of cut have significant influence on the tool life (*T*) (*p*-value < 0.05).

The mathematical model (3) is shown graphically in Figure 9 in order to analyze the influence of the cutting speed, feed rate and depth of cut on the tool life (*T*). From the mutual comparison of the exponents of the cutting speed, feed rate and depth of cut, it follows that tool life is more sensitive to changes in the cutting speed and depth of cut, and less sensitive to changes in the feed rate. As the cutting speed, depth of cut and feed rate increase, the tool life (*T*) decreases.

Table 11 shows a comparison of the results obtained via the experiment and the results obtained via the mathematical model. The diagram in Figure 10 is a graphical representation of the difference between the results of the experiment and mathematical model for tool life.

Table 11. Experiment results, model results and residues for *T*.

Experiment Number	**Experiment *T*, min**	**Mathematical Model *T*, min**	**Residue**
1	7.5	6.74	0.76
2	2.45	2.42	0.03
3	2.81	3.85	−1.04
4	1.31	1.38	−0.07
5	13.7	12.29	1.41
6	3.8	4.42	−0.62
7	2.87	2.63	0.24
8	1.13	0.95	0.18
9	7.49	9.69	−2.21
10	8.39	5.53	2.86
11	2.19	2.08	0.11
12	1.02	1.19	−0.17

Table 11. *Cont.*

Experiment Number	Experiment *T*, min	Mathematical Model *T*, min	Residue
13	2.83	2.91	−0.08
14	2.94	2.91	0.03
15	2.91	2.91	0.00

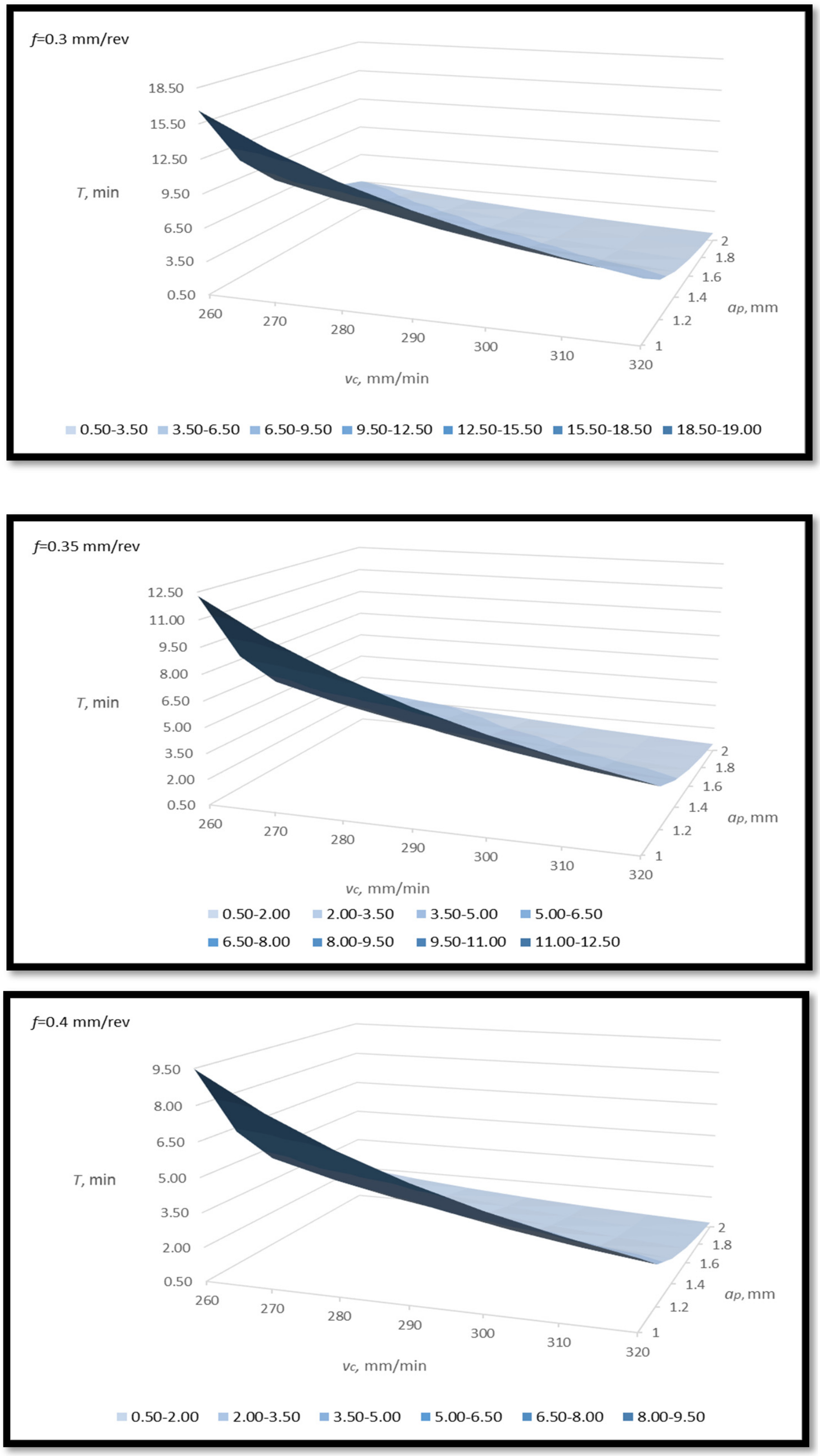

Figure 9. Achievable tool life (*T*) when turning martensitic stainless steel X20Cr13 under.

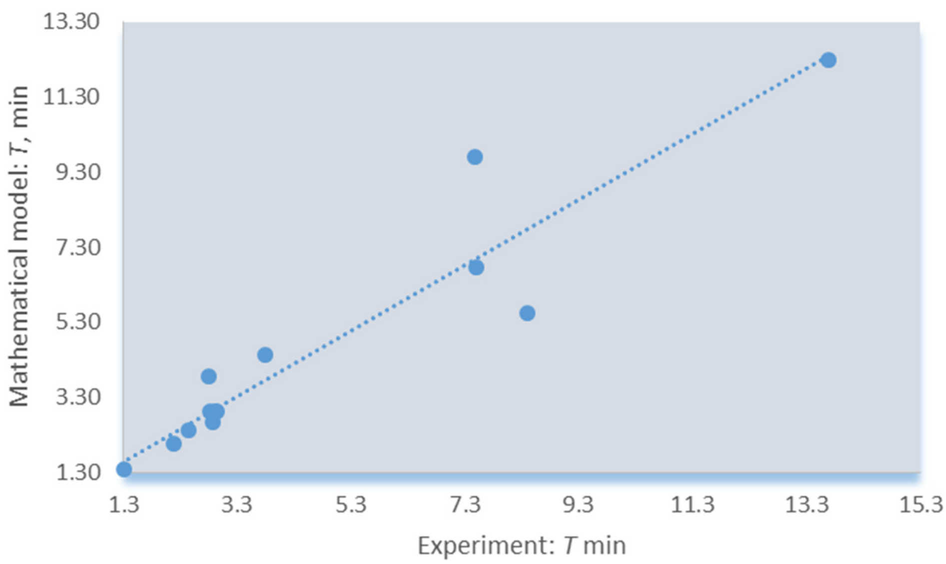

Figure 10. Experiment–mathematical model comparison diagram for *T*.

MQL + vortex conditions for feed rate (f) = 0.3, 0.35 and 0.4 mm/rev: (v_c) cutting speed, (a_p) depth of cut.

2.2.3. The Effect of the Vortex Tube on Lowering the Temperature

For cooling with a vortex tube, the temperature and the capacity of cold air that will be brought to the cutting zone should be determined. As the flow of cold air increases, the air is cooler. During machining, the cold air should provide two functions: effective removal of chips and cooling. A chip remaining on the workpiece causes its underlining under the cutting tool and damages the machined surface. That is why a larger flow of cold air was chosen. For the used vortex tube system with an air flow of 708 L/min, a proportion of cold air of 80% of the inlet flow, or 566.4 L/min, was determined. The remaining 20% of the inlet flow exits at the hot end of the vortex tube. With the inlet air pressure of 0.69 MPa, a temperature drop of −29 °C can be achieved in regard to the inlet air temperature. Considering the room temperature of 21 °C during the experiments, the temperature of the outlet cold air flow was approximately −8 °C, Figure 11. The average temperature reached at the tool–workpiece interface was 52.8 °C. With the MQL technique, the average temperature was higher than 90.9 °C, Figure 12. Therefore, in addition to ensuring the removal of chips from the cutting zone, the use of a vortex tube has achieved an additional drop in temperature at the tool–workpiece interface by −38.1 °C. This result may not be precise because oil mist affects the temperature measurement, but oil mist exists in both MQL and MQL + vortex tube cooling. So, Figures 11 and 12 describe the average temperature trend—the average temperature decrease in MQL + vortex tube cooling compared to MQL. The thermal imaging camera ThermaCAM S65 manufactured by FLIR Systems was used for non-contact temperature measurement.

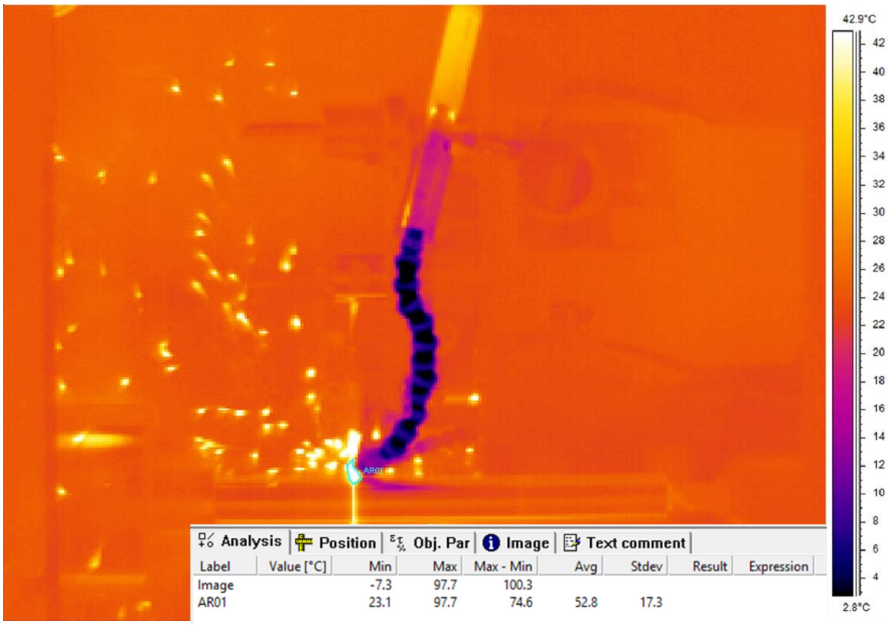

Figure 11. Temperatures in the cutting zone: MQL + vortex tube condition.

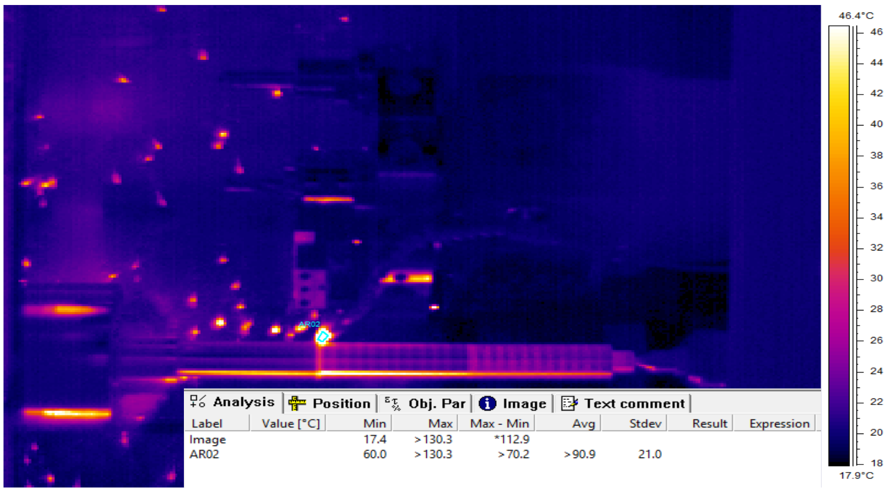

Figure 12. Temperatures in the cutting zone: MQL condition.

3. Conclusions

Conventional MWFs based on mineral oils are harmful to the environment and human health and introduce large additional costs into production. For these reasons, they are recognized as the main unsustainable element of the machining process, so alternative cooling and lubrication techniques are increasingly being developed.

The cooling condition MQL + vortex tube was applied in the presented experimental procedure for turning martensitic stainless steel X20Cr13 according to the Box–Behnken design (15 experiments) to establish the mathematical models between the machining responses *Ra*, *Rz* and *T* and the cutting speed, feed rate and depth of cut. The cutting speed (v_c) = 260, 290 and 320 m/min, feed rate (f) = 0.3, 0.35 and 0.4 mm/rev and depth of cut (a_p) = 1, 1.5 and 2 mm were selected as cutting parameters.

According to the ANOVA results for the selected cutting parameters used in the Box–Behnken design, exponential models for *Ra*, *Rz* and *T* were obtained.

The ANOVA results showed that only the feed rate has a significant influence on *Ra* and *Rz*; as the feed rate increases, the roughness parameter *Ra* and *Rz* increases. The tool life (T) was most influenced by the cutting speed, followed by the depth of cut and feed rate. As the cutting speed, depth of cut and feed rate increases, the tool life (T) decreases.

A comparison of the results of Ra, Rz and T obtained via experiment and those obtained via mathematical models gives the conclusion that the "residue" values are very small, so the established models are representative.

For the used vortex tube system with an air flow of 708 L/min and the inlet air pressure of 0.69 MPa, a temperature drop of −29 °C can be achieved in regards to the inlet air temperature of 21 °C.

The main conclusions are:

1. The implementation of the experiments made it possible to consider the insufficiently researched MQL lubrication technique supported by vortex tube cooling when turning martensitic stainless steel X20Cr13. Based on the analysis of the impact on machinability, the mathematical models are defined.
2. Models provide a reliable basis for optimizing the turning of martensitic stainless steel X20Cr13 in the MQL + vortex cooling condition.
3. The temperature of the outlet cold air flow was approximately −8 °C. The use of the vortex tube under the MQL + vortex tube condition achieved an additional drop in temperature at the tool –workpiece interface by −38.1 °C.
4. Finally, the MQL lubrication technique with vortex tube cooling can be recommended for the turning of martensitic stainless steel X20Cr13. It has been confirmed that the use of conventional MWFs can be excluded when turning martensitic stainless steels. Furthermore, this alternative cooling technique has a positive effect on two aspects of sustainability: the environment and health protection.

For future research, the effect of the third aspect, costs, and input parameters such as nozzle distance and angle, can be investigated.

Author Contributions: Conceptualization, G.Š.V., T.K. and G.C.; methodology, G.C.; software, G.Š.V. and T.K.; validation, G.C.; formal analysis, G.Š.V. and T.K.; investigation, G.Š.V. and T.K.; writing—original draft preparation, G.Š.V., T.K. and M.F.; writing—review and editing, G.Š.V., T.K. and M.F.; visualization, M.F.; supervision, G.C.; project administration, G.Š.V. and G.C.; funding acquisition, G.Š.V. and G.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work has been partially supported by University of Rijeka, grant number uniri-mladi-technic-20-12 and grant number uniri-tehnic-18-293. The APC was funded by University of Rijeka, Croatia. The authors would like to thank all the funding received.

Data Availability Statement: Details regarding the data can be obtained by emailing the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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