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ORIGINAL ARTICLE

Analyzing machining parameters for commercially pure titanium (Grade 2), cooled using minimum quantity lubrication assisted by a Ranque-Hilsch vortex tube

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Abstract In pursuit of developing environmentally friendly techniques for machining, a lot of hard work has been done by researchers all over the world, and many fruitful results have been obtained. When focussing on cooling techniques, minimum quantity lubrication (MQL) is one such development that has proven to be highly useful in leading to a greener manufacturing process. The need of the hour is not just to compare its (MQL) benefits to dry and flood cooling. Rather, certain improvements need to be introduced in the MQL process to make it more effective and improve its performance. In this study, a similar effort has been made by introducing a Ranque-Hilsch vortex tube into the MQL process. Turning of commercially pure titanium (Grade 2) was commenced using uncoated tungsten carbide inserts. Variations in speed, feed and depth of cut were made. The experiments were designed using response surface methodology, and analysis of variance (ANOVA) was performed to identify the effect of the input parameters on the responses, i.e., surface roughness, cutting force, power and flank wear. Optimizations of the results proved that the Ranque-Hilsch vortex tube made significant improvements in the results and was suggested as a better method. These predictions were experimentally validated, thus making the MQL process more effective with a negligible cost addition and heading to a greener future in manufacturing industry.

Keywords Minimum quantity lubrication · Ranque-Hilsch vortex tube · Surface roughness · Cutting force · Power · Flank wear

1 Introduction and background work

In any manufacturing industry, the productivity and overall economy of any process depends directly on factors such as the tool wear, surface finish, cutting force, cutting power consumption, temperature, etc. While cutting, all the power consumption gets directly or indirectly converted into heat which elevates the temperature of the cutting zone. Thus, the cooling process becomes an integral part of any machining operation. As a result of the economic and ecological pressures, the industry seeks for newer methods to minimize the consumption of harmful lubricants. Safeguarding the environment and the human health is the top priority in the present day industrial scenario. This is the main aim with which the international standard 14001 has been set up [1–4]. Minimum quantity lubrication or MQL is a cooling process for the metal cutting operations that makes use of minuscule quantities of the lubricant. Various researchers have contributed in the field of MQL. Igoitawa et al. made a spectacular effort to further optimize the MQL process. The effect of water as well as the lubricant was studied when used in combination and individually. It was concluded that the lubricant alone gave good lubrication but poor cooling. Water had a good chilling effect, and when used with a suitable ester as a lubricant, created excellent boundary layer was formed that led to the improved results [5]. While using MQL technique for grinding cast iron and EN 24 steel, Kalita et al. made use of nano-particles in variable concentrations. The results were shown in terms of specific energy and friction coefficients. It was noticed that as the concentration of the nano-particles increased, the specific

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Table 1 Experimental results

V_C (m/min)	f (mm/rev)	ae (mm)	Cooling condition	R_a (μm)	F_C (N)	P (Watts)	V_{bmax} (μm)
275	0.13	0.5	MQL	0.49	156	716	221.82
250	0.05	0.4	MQL	0.34	94	390	134.39
300	0.13	0.4	MQL	0.75	165	825	224.11
300	0.09	0.5	MQL	1.13	154	704	177.86
300	0.05	0.4	MQL	0.42	80	399	160.95
275	0.05	0.5	MQL	0.44	102	467	176
300	0.09	0.3	MQL	0.46	94	468	175.82
275	0.05	0.3	MQL	0.27	68	344	157.57
250	0.09	0.3	MQL	0.47	85	354	175.17
275	0.13	0.3	MQL	0.7	115	528	208.71
275	0.09	0.4	MQL	0.45	115	526	179.64
250	0.09	0.5	MQL	0.58	126	525	180.25
250	0.13	0.4	MQL	0.9	150	683	197.4
250	0.09	0.5	RHVT MQL	0.35	121	504	147.54
300	0.13	0.4	RHVT MQL	0.52	140	699	189.14
275	0.05	0.5	RHVT MQL	0.42	95	435	168.06
300	0.05	0.4	RHVT MQL	0.35	74	372	148
250	0.13	0.4	RHVT MQL	0.6	135	610	176.17
275	0.09	0.4	RHVT MQL	0.4	110	506	140.24
275	0.13	0.5	RHVT MQL	0.5	135	675	179.24
275	0.13	0.3	RHVT MQL	0.38	104	479	142.65
250	0.09	0.3	RHVT MQL	0.35	97	404	145.74
250	0.05	0.4	RHVT MQL	0.28	96	402	81.86
300	0.09	0.5	RHVT MQL	0.55	121	604	133.32
275	0.05	0.3	RHVT MQL	0.22	58	265	170.84
300	0.09	0.3	RHVT MQL	0.42	89	444	150.41

energy as well as the friction coefficient got reduced significantly [6]. When focussing on the cutting forces and residual stresses, MQL leads to significant reduction in the residual stresses as well as cutting temperatures while gives similar results to the flood cooling when compared in terms of the cutting forces. Also, the flow rate of the coolant leads to improved results only up to a certain level, above which the improvement becomes insignificant [7]. From the review on MQL process, it is very much evident that the MQL process leads to a reduction in the temperature of the cutting zone along with favourable work-chip and work-tool interactions. This leads to a significant reduction in the tool wear as well as the surface roughness. There is significant reduction in friction as well due to the combined cooling and lubricating effect of the process, accounting for the reduction in the cutting power and cutting forces.

It would be very interesting to see further the effects that the vortex principle-assisted cooling might have in addition to the MQL-cooled process. In this study, efforts have been made to improve the performance of the MQL process using a Ranque-Hilsch vortex tube (RHVT). To begin with, an RHVT is a device that simply separates an incoming stream of compressed gas into two separate streams, one colder and the other warmer than the incoming stream. It comprises of an inlet nozzle, a cold air outlet, a hot air outlet with a control valve and a vortex chamber. This vortex chamber is specifically designed to accelerate the incoming stream of air to a high rate of rotation [8]. In their study to check the effectiveness of an RHVT for cooling during machining, Selek et al. made use of the infrared thermography method. The experiments were performed at different speeds and cutting depths. The results proved that the RHVT-assisted machining resulted in a much lower temperature at a cutting zone as compared to the other cooling techniques [9]. Liu and Chou made use of vortex tube air cooling for hyper eutectic Al-Si alloys. It was concluded that the vortex tube cooling reduced the tool wear depending upon the machining conditions [10]. Although the available literature clearly indicates that the RHVT helps in effective cooling, but very negligible amount of work is available where the combined effects of an RHVT and MQL have been studied. Titanium and its alloys possess certain properties like their impressive specific strength. This imparts them

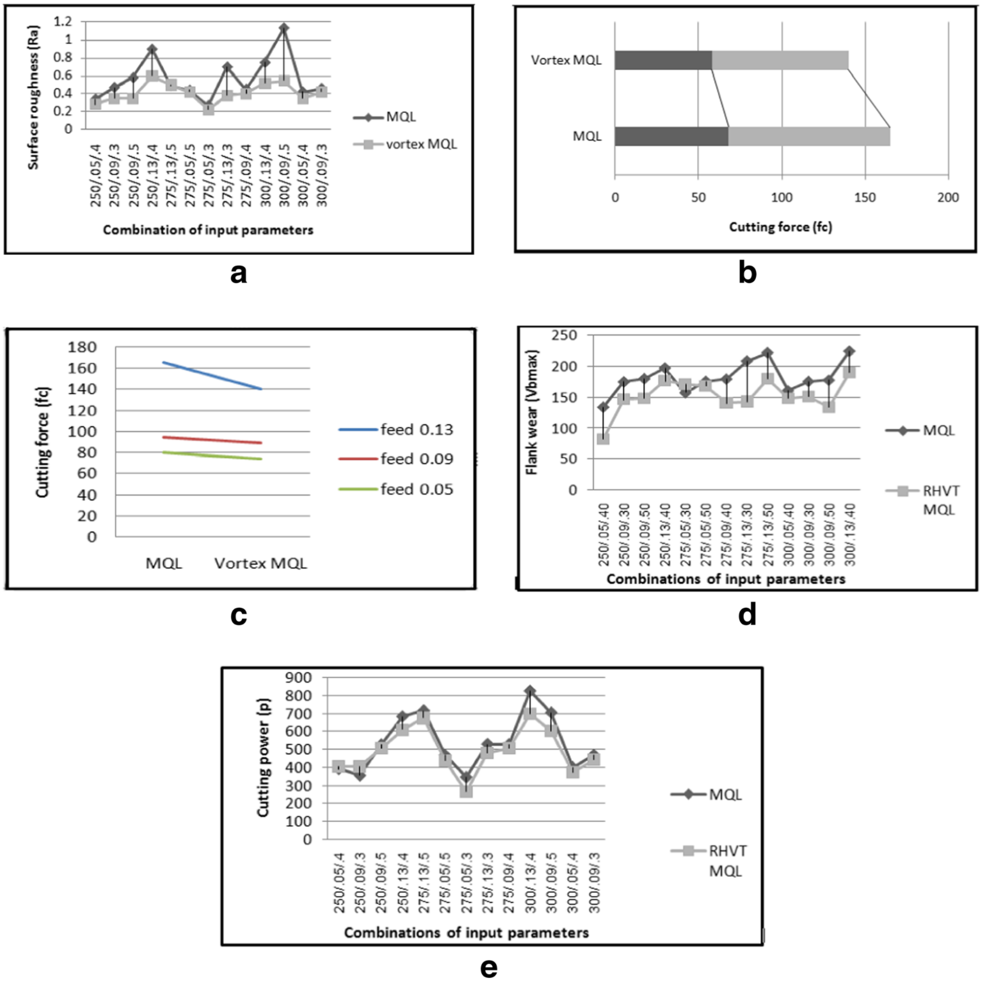

Fig. 1 Observed results. **a** Comparison of MQL and RHVT MQL for surface roughness (R_a). **b** Cutting force (F_C) range for MQL and RHVT MQL. **c** Comparison for cutting force (F_C) at different feed levels. **d** Comparison of MQL and RHVT MQL for flank wear (V_{bmax}). **e** Comparison of MQL and RHVT MQL for cutting power (p)

qualities like corrosion resistance as well as resistance to fracture, thus making them very suitable contenders for aerospace applications. The extraction process of titanium is very difficult, making it costly. Due to the hard nature, it cannot be machined to larger depths. As a result, very fine and thin chips are produced, leading to a problematic machining process. The cutting temperature also tends to be very high as a result of the low thermal conductivity. When talking in terms of the tool wear, titanium and its alloys are highly reactive to the tool material that leads to a higher tool wear. The high reactivity of titanium to oxygen and nitrogen leads to hardening, which also increases the wear rate. The high pressure cooling of titanium using water soluble lubricants results in much better results when compared to wet cooling process. The tool life under such conditions is known to improve by at least 250 %. Cooling using only oil proves to be less beneficial [11]. Priarone et al. performed milling experiments on gamma titanium aluminide intermetallic alloy. Different types of lubricating conditions were compared including dry, wet and MQL. It was shown that MQL gave the best results in terms of tool wear and surface roughness even when compared to wet machining [12]. Islam et al. made a very interesting study on the effect of cooling techniques on the surface finish and dimensional accuracy of titanium parts. Both experimental and analytical analyses were performed. It was shown that the cryogenic cooling led to the minimum diametric error and the circularity, while least effect on the surface roughness [13]. Liu et al. made an impressive study on the hard turning of Ti-6Al-4V cooled using a cold air gun using compressed air. It was noticed that the compressed air led to better penetration as compared to the traditional cooling producing wrinkled and broken chips [14]. Sharma et al., after an exhaustive study on the work done in the field of MQL, concluded that MQL leads to lowering of the cutting temperature which in turn results improved tool life as well as the surface roughness. The study was made on turning, milling, drilling and grinding of different types of metal alloys including steel, titanium, inconel, aluminium, etc. [15]. Ginting et al. [16] also studied on the various options available for cooling using compressed air. Vortex tube cooling was taken up as one of the options besides cryogenic (LN2) cooling which is more expensive and the thermoelectric cooling which is still in its developmental

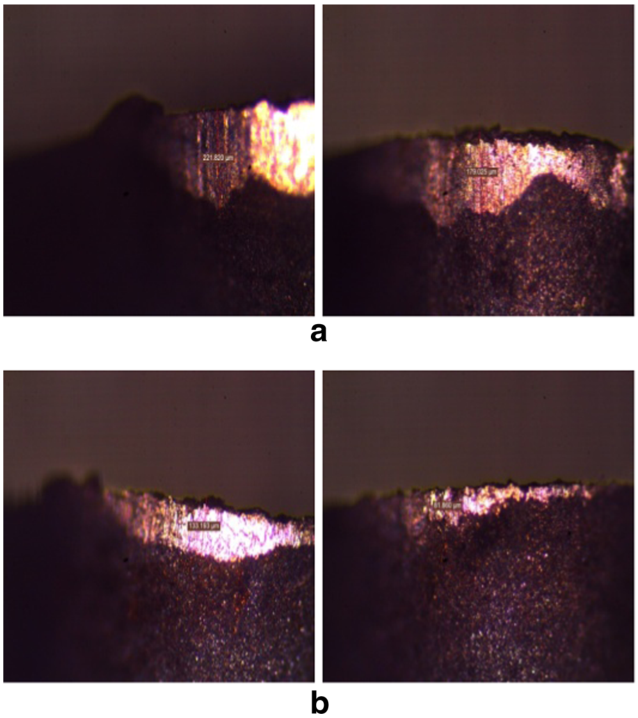

Fig. 2 Comparison of flank wear (V_{bmax}) between MQL (*left*) and RHVT MQL (*right*) at $V_C = 275$ m/min, $f = 0.13$ mm/rev and ae = 0.50 mm (**a**) and $V_C = 250$ m/min, $f = 0.05$ mm/rev and ae = 0.40 mm (**b**)

phase. It has been stated that the RHVT along with the MQL may lead to impressive results when studied in details on different industrial materials.

Although there is a fair amount of literature available on titanium alloys, but very little work is there on the commercially pure titanium (Grade 2). But this does not make it less important, as it is the most highly used commercially pure titanium grade. Apart from this, it is totally resistant to corrosion. Another important characteristic of this grade is its biocompatibility, making it very important for the medical field. Thus, it would be interesting as well as enlightening to study the machining characteristics of commercially pure titanium (Grade 2) at higher speeds and studying the additional cooling effect of an RHVT on the output parameters such as surface roughness, cutting force, power and flank wear. It can be pointed out that the RHVT cooling with dry air lacks the lubrication effect. The use of a water soluble lubricant-based MQL technique in combination with RHVT shall lead to better results. Besides the cooling air effect, the chilling effect of water along with the lubrication effect may give results better than the flooding technique. Thus, the present study focuses on the use of an RHVT.

Table 2 ANOVA summary for results

Factors	F_c (N)	V_{bmax} (mm)	R_a (µm)	p
R-squared	0.8867	0.6362	0.56	0.8957
Adj. *R*-squared	0.8651	0.5669	0.4762	0.8758
Pred. *R*-squared	0.8225	0.4312	0.3148	0.8364
Adeq. precision	22.129	10.164	8.97	22.089
Model *F* value	41.08	9.18	6.68	45.07

2 Experimental setup

For the experimentation, commercially pure titanium (Grade 2) was chosen as the work material. The choice was made on the basis of lesser literature available, in spite of being the most widely used commercially pure titanium grade. It consists of nearly 99 % titanium while the remaining composition is divided between ferrous, nitrogen, hydrogen and oxygen. Uncoated carbide inserts were used for performing the experimentation. The relief angle was 7° while the nose radius was 0.8 mm. The insert material was chosen, keeping the low-cost experimentation in mind, apart from the eco-friendliness. It was also known that the PVD-coated carbides and ceramics have a low fracture toughness as well as the thermal conductivity, making them less favourable to machine titanium alloys [17]. Titanium bars of length 150 mm were used while the cutting length was maintained at a constant 100 mm for all the experiments. Turning was performed on a BATLIBOI Sprint 20TC model CNC with a spindle motor of 11 kw and spindle speeds in the range of 30–4000 rpm. The force and power measurements were made using the TeLC DKM2010 dynamometer. The tool wear was measured using the Leica DFC 290 tool maker's microscope, while the surface roughness was measured using the Mitutoyo SJ 301 surface roughness tester. Essen engineers 002H model vortex tube was used to reduce the air temperature before mixing it with the coolant. The main aim was to compare the output parameters for MQL performed at lowered temperature with ambient temperatures. The speed, feed as well as the depth of cut were varied in three levels as shown in Table 3. The coolant flow rate was kept stable at 30 ml/h at a constant pressure of 6 bars. The lubricant concentration was kept at 5 %. The experimental design and parametric optimization was carried out using the response surface methodology. The lone categorical factor, cooling condition, was varies over two levels. A total of 26 experiments were performed as per the Box-Behnken design. Each factor or independent variable is placed at one of the three equally spaced values usually coded −1, 0 and +1.

3 Results and discussions

The experimental results of all the output parameters were statistically examined for adequacy and significance. ANOVA technique was brought into use. Table 1 shows the results obtained after the experimentations.

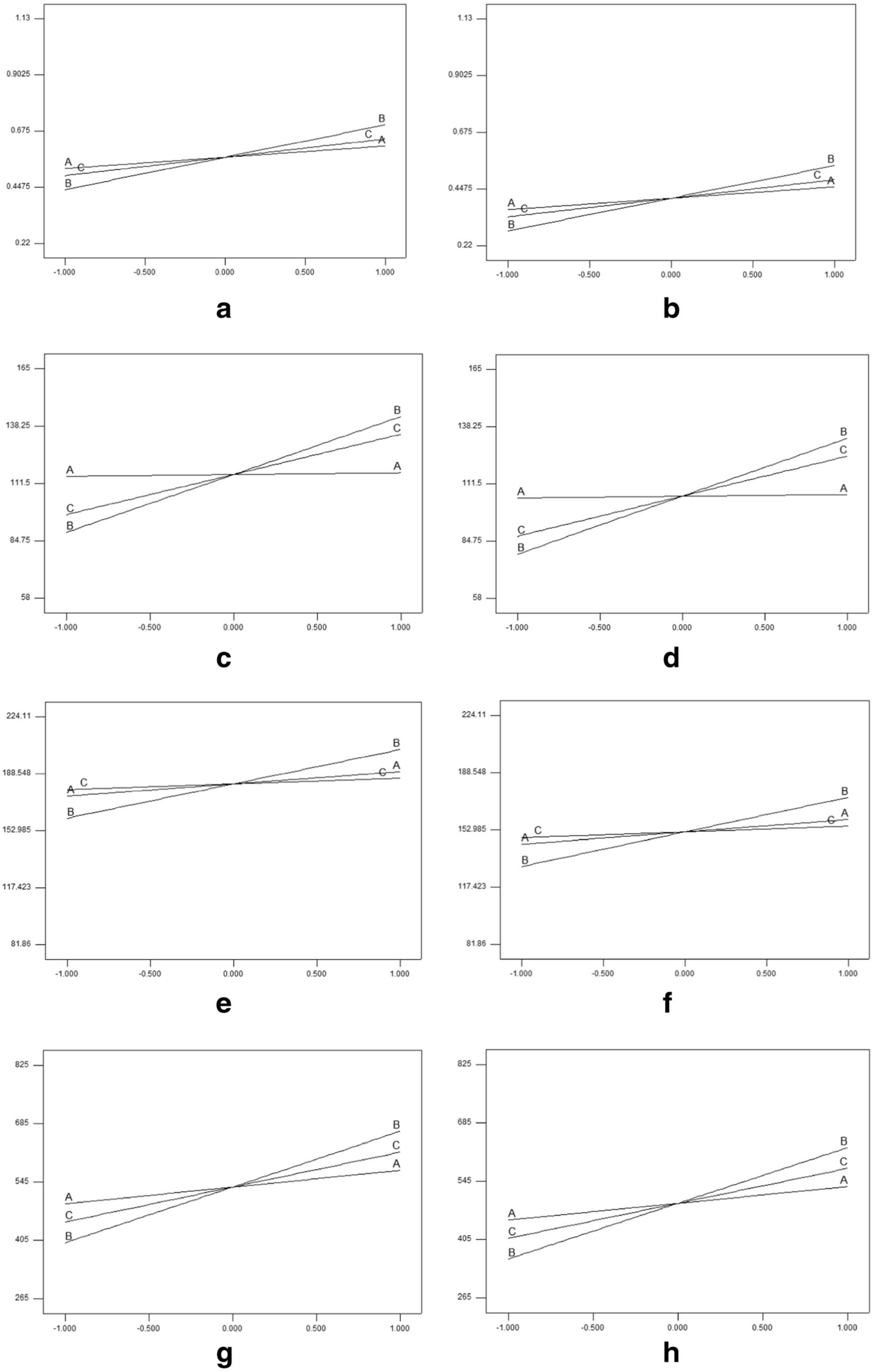

Fig. 3 **a** Perturbation curves (R_a) for MQL cooling. **b** Perturbation curves (R_a) for vortex MQL cooling. **c** Perturbation curves (F_C) for MQL cooling. **d** Perturbation curves (F_C) for vortex MQL cooling. **e** Perturbation curves (V_{bmax}) for MQL cooling. **f** Perturbation curves (V_{bmax}) for vortex MQL cooling. **g** Perturbation curves (p) for MQL cooling. **h** Perturbation curves (p) for vortex MQL cooling at $V_C = 275$ m/min, $f = 0.09$ mm/rev and ae = 0.4 mm

Surface finish is a very important parameter in the manufacturing industry. It can severely affect the manufacturing cost as well as the performance of a mechanical part. As a result, it was considered as one of the response parameters to be studied. Figure 1a depicts the comparison of surface roughness values for both the cooling processes. It can clearly be seen that RHVT MQL resulted in lower surface roughness values when compared to MQL process for all the combinations of parameters. This decrease in the surface roughness (R_a) for the RHVT MQL process may be explained on the

Table 3 Regression equations for the output parameters

Cooling type	Equations
MQL	$R_a = -0.52 + 1.82\text{E-}00 \times V_C + 3.28 \times f + 0.74 \times \text{ae}$
RHVT MQL	$R_a = -0.68 + 1.82\text{E-}00 \times V_C + 3.28 \times f + 0.74 \times \text{ae}$
MQL	$F_C = -29.13 + 0.03 \times V_C + 676.56 \times f + 187.50 \times \text{ae}$
RHVT MQL	$F_C = -39.05 + 0.03 \times V_C + 676.56 \times f + 187.50 \times \text{ae}$
MQL	$V_{\text{bmax}} = +35.70 + 0.30 \times V_C + 535.23 \times f + 35.60 \times \text{ae}$
RHVT MQL	$V_{\text{bmax}} = +5.28 + 0.30 \times V_C + 535.23 \times f + 35.60 \times \text{ae}$
MQL	$p = -546.14 + 1.60 \times V_C + 3345.31 \times f + 840.00 \times \text{ae}$
RHVT MQL	$p = -586.90 + 1.60 \times V_C + 3345.31 \times f + 840.00 \times \text{d.o.c}$

basis of the reduction in temperature. The pressurized air causes better cooling at the cutting zone. The thermal softening of the work material also may have decreased to a certain extent along with the reduction in the friction between the tool and the workpiece. Altogether validating the improvement in the surface roughness (R_a). Another observation made was that at higher levels of feed (peak points in the Fig. 1a), the variation in the surface roughness (R_a) values between the two cooling processes was more when compared to the lower feeds. It can thus be concluded that the effectiveness of the RHVT MQL process improves at higher levels of feed (f). Figure 1b shows the ranges of cutting forces (F_C) obtained as a result of the experimentation for both the cooling techniques. It is clearly visible that the RHVT MQL resulted in the cutting forces of comparatively lower magnitudes. The maximum value of cutting force (F_C) at the same parameters came out to be 15 % lower for the RHVT MQL cooling, which is a quite significant reduction. Figure 1c shows the comparisons of the cutting forces (F_C) at different levels of feed (f) for both MQL and vortex MQL at 300 m/min. The difference appears to be more at higher levels of feed while it is somewhat similar at the lower levels of feed for all the levels of the cutting speed (V_C). Similar trend occurred at the other levels of cutting speed as well. The reduction of cutting forces (F_C) can be explained on the basis of the reduced temperature at the cutting zone. The reduction in temperature leads to reduction in the friction produced, which in turn leads to the reduction in the cutting forces (F_C). V_{bmax} was brought into use instead of V_{bavg}. Although V_{bavg} is statistically consistent, but in this case, none of the experiments led to a uniform wear. In such cases, using the average value may provide misleading results. Hence, V_{bmax} was brought into use for comparing the results. Figures 1d and 2 show the comparisons of tool wear (V_{bmax}) for both MQL and vortex MQL techniques at the different cutting parameters. Figure 4a, b shows the microscopic views for flank wear for both MQL and vortex MQL techniques. Usage of a vortex tube significantly reduced the tool wear (V_{bmax}) values. The chilling effect of the droplets of cold water droplets accompanied with proper lubrication of the cutting zone evidently may have led to better cooling of the work-tool interface. Temperature plays a highly significant role in influencing the properties of the carbide tools related to wear [16]. Such a reduction of the temperature at the cutting zone may have lowered the stickiness of the work material, maintaining the hardness and strength in addition. The above mentioned conditions certainly reduced the work tool adhesion, resulting in an increase in the tool life [18]. Moreover, at such high levels of cutting speeds, feed (f) came out to be the most important factor affecting the flank wear (V_{bmax}). At higher levels of the feed (f), higher flank (V_{bmax}) wear was noted. It was also seen that at higher feed (f), the difference in the performance of the MQL and the vortex MQL processes became more. Seeing the results, the RHVT MQL process for cooling can be considered more suitable.

Cutting power (p) is yet another important parameter, especially when it comes to higher speed and rough operations. Selection of the machine with the most suitable power output helps in making the cutting operation more and more cost effective. It also helps in the selection of the most suitable machining parameters so as to obtain the best possible material removal rate while taking the tool capacity in mind. Scientifically, the cutting power is calculated as shown in Eq. 1.

$$p = Fc * Vc / 60{,}000, \tag{1}$$

where F_C is the cutting force (N) and V_C is the cutting speed (m/min). It was also known that $F_C = k_C * \text{ae} * f$. Where ae is the depth of cut (mm), f is the feed (mm/rev) and k_C is the specific cutting energy coefficient (N/mm^2). This gives rise to Eq. 2.

$$p = k_c * \text{ae} * f * Vc / 60{,}000 \tag{2}$$

This directly states the direct dependence of the cutting power (p) on the cutting speed (V_C), feed (f) as well as the depth of cut (ae). Figure 1e shows the comparison of power consumption (p) between the MQL and the RHVT MQL process. It was noticed that the power consumption experienced a

Table 4 Optimized results (OP1)

Number	V_C	f	ae	Cooling	R_a	F_C	p	V_{bmax}	Desirability
1.	271	0.05	0.30	RHVT	0.198	64.20	268.41	125.65	0.906
2.	271	0.05	0.30	RHVT	0.197	64.35	268.00	125.58	0.906
3.	272	0.05	0.30	RHVT	0.199	63.68	269.82	125.92	0.906

Table 5 Optimized results (OP2)

Number	V_C	f	ae	Cooling	R_a	F_C	p	V_{bmax}	Desirability
1.	300	0.08	0.46	RHVT	0.45	107.74	536.83	154.25	0.598
2.	300	0.08	0.46	RHVT	0.45	107.61	534.95	154.27	0.598
3.	294	0.07	0.41	MQL	0.55	110.65	513.80	178.93	0.502

similar decrease as the cutting force (Fc) with the application of the vortex principle to the cooling process. The lowered temperature led to reduced friction, which ultimately reduced the power consumption. The reduction in power may also be considered as a result of the decreased flank wear (V_{bmax}).

The Table 2 summarises the ANOVA results for the output parameters while the Table 2 lists the regression equations. Figure 3 displays the perturbation curves for the various parameters, all suggesting RHVT MQL as the better option.

4 Optimization and validation

After the complete analysis of all the responses, optimization of the input parameters was carried out. The desirability approach was used to carry out the optimization. This approach mostly finds its use where single or multiple objective optimizations are done to find the optimum parametric combinations. This approach does not allow the clashing of responses, when compared to the single response optimizations.

4.1 Optimization with the full range of parameters (OP1)

For this condition, all the input parameters were allowed to vary within the full range of their variability. While, all the response parameters i.e. the surface roughness (R_a), cutting force (F_C), cutting power (p) and flank wear (V_{bmax}) were minimized to get the best results. Table 3 shows the three most optimum results with the highest desirability. It showed that RHVT MQL gave the best results with feed (f) and D.O.C. (ae) taking their minimum values while the cutting speed (V_C) with an intermediate value of 271 m/min, with a desirability of .906.

4.2 Optimization for minimizing the machining time (OP2)

In this case, the constraints were selected in order to optimize the parameters for minimizing the machining time. All the input parameters were maximized as that would lead to minimum time consumption. The response parameters were taken to be minimum as in the previous case. The results in the Table 4 again confirmed the RHVT MQL cooling as the more dominating technique out of the two. Although the desirability of the process came out to be as low as 0.598.

4.3 Validation

Three validation tests were conducted for both the sets of optimum parameters. The purpose of such tests was to confirm the conclusions made by the model. Table 5 shows the comparison between the actual as well as the predicted results. It shows that the actual results form an agreement with the predicted results. Thus, it would be fair to conclude that the above model may be used for prediction of the output parameters while machining commercially pure titanium (Table 6).

5 Conclusions

1. Using an RHVT in addition to the MQL cooling process led to improvement in the surface finish (R_a) where the highest obtained value at same parameters was found lowered by 15 % while the lowest value lowered by 18 % when compared for both MQL and RHVT processes.
2. The cutting force (F_C) and cutting power (p) also reduced significantly for the vortex cooling. This validates the

Table 6 Validation of results for both OP1 and OP2 (*Pred* predicted value, *Act* experimental value)

Exp.	Pred. R_a	Act. R_a	Pred. F_C	Act. F_C	Pred. p	Act p	Pred. V_{bmax}	Act. V_{bmax}
OP1 (1)	0.198	0.206	64.20	68.49	268.41	279.44	125.65	131.14
OP1 (2)	0.198	0.206	64.20	67.86	268.41	275.32	125.65	130.65
OP1 (3)	0.198	0.205	64.20	68.04	268.41	277.89	125.65	134.55
OP2 (1)	0.45	0.47	107.74	115.04	536.83	566.76	154.25	162.12
OP2 (2)	0.45	0.48	107.74	114.78	536.83	560.45	154.25	162.52
OP2 (3)	0.45	0.48	107.74	115.32	536.83	565.87	154.25	161.94

importance of lowered temperature at the cutting zone in reducing the friction between the cutting tool and the workpiece, ultimately leading to lowered force and power.

3. Feed (f) plays the most important role in affecting cutting force (F_C) and cutting power (p). At higher feed (f), the difference in the cutting force values is higher when compared to the lower feeds, which is in line with the known facts.
4. Flank wear (V_{bmax}) reduced significantly with the vortex MQL process. Again, feed (f) was found out as the most significant factor while the cutting speed (V_C) and depth of cut (ae) remained insignificant.
5. The AVOVA analysis done for all the responses made full agreement with the experimental results, confirming the model's validity.
6. Optimization was done for two types of constrained values depending upon the user priority. First with the entire range of parameters and the second for minimizing the time of machining. Both yielded vortex MQL as the better one amongst the two cooling techniques.
7. Validation tests conducted for both types of optimized parameters gave very similar results to the predicted ones. The error in both cases was under 7 %. Thus, the model can turn out to be useful for machining commercially pure titanium under similar parameters.

6 Nomenclature

MQL—Minimum quantity lubrication
RHVT—Ranque-Hilsch vortex tube
V_C—Cutting speed
f—Feed
ae—Depth of cut
R_a—Surface roughness
F_C—Cutting force
p—Cutting power
V_{bmax}—Maximum flank wear

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