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MULTI-CRITERIA OPTIMIZATION OF TURNING OF MARTENSITIC STAINLESS STEEL FOR SUSTAINABILITY

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Abstract

A modern production strategy faces the increasing challenges of practicing green production without sacrificing machining performance. Thus, this paper compares emulsion cooling, minimum quantity lubrication without and with a Ranque-Hilsch vortex tube when turning martensitic stainless steel X20Cr13. Experimental tests were organized corresponding to Taguchi orthogonal array $L_{27}(3^4)$. The Taguchi based entropy weighted grey relational analysis was exploited to acquire the optimum combination of cutting speed, feed, depth of cut and cooling method that concurrently minimize surface roughness and tool life while maximizing material removal rate. The combination of minimum quantity lubrication with Ranque-Hilsch vortex tube confirmed to be the best cooling method. Hence, the use of classic metalworking fluids when turning martensitic stainless steels can be excluded, which is important for reducing environmental pollution and hence for machining sustainability.

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Key Words: Turning, Martensitic Stainless Steel, Sustainability, Multi-Criteria Optimization, Entropy Weighted Grey Relational Analysis, Taguchi Method

1. INTRODUCTION

The stainless steels are difficult-to-cut materials, so a high flow of metalworking fluid (MWF) should be used in their machining [1]. The MWF must provide cooling to prevent the overheating of surface being machined. In the event of overheating, which manifests itself as a nuanced coloration of machined surface, the corrosion resistance can be reduced. Also, the MWF must provide lubrication to decrease tool wear and to help flushing the chips [2].

The MWFs market is estimated to reach $ 9.74 billion by 2020, with an annual growth rate of 3.2 % between 2015 and 2020 [3]. However, it is necessary to take into account the influence of MWFs not only on the machined part but also on the whole environment, primarily on the working surrounding. Namely, the MWFs contain large amounts of ingredients that are harmful to the environment and human health. Hence, they are classified as hazardous waste [4] and must be disposed of safely [5]. Nowadays, the costs of proper disposal of waste MWFs are higher than their purchase price.

Increasingly stringent environmental and occupational safety standards are a growing reason for replacing the use of conventional MWFs with alternative cooling and/or lubrication methods in machining, which is the reason for the development and application of so-called "green manufacturing". Its main goals are environmental protection, protection of workers, reduction of the use of MWFs and reduction of production costs achieved precisely by reducing the costs associated with MWFs. In this regard, minimum quantity lubrication (MQL) and chilled compressed air cooling are attracting increasing attention.

MQL involves consuming 5-50 millilitres of pure vegetable or synthetic oil per hour with almost no residue, while the usual wet machining consumes several litres of MWF per minute. The oil is dispersed in a stream of compressed air or, simply, in the form of an aerosol. More than 100 published papers in 2015 alone testify to the importance of MQL [6].

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Chilled compressed air cooling is considered the cleanest and most environmentally friendly [7]. It is most often carried out by means of a counter-flow Ranque-Hilsch vortex tube (RHVT). Compressed air at ambient temperature tangentially enters the vortex tube where it splits into two swirling streams: inner colder and outer warmer, which is known as the Ranque-Hilsch effect. The cold air stream can reach the lowest temperature up to -50 °C while the hot air stream can reach 100 °C. The RHVT is simple, inexpensive, compact, light and quiet to operate [8].

Investigations have shown the benefits of RHVT cooling in competition with the wet and dry machining. Ginting et al. [9] stated that the replacement of wet machining with RHVT cooling can save 80 cents apiece. Taha et al. [10] studied the effect of RHVT cooling on surface roughness and power consumption in dry turning. The results showed that this cooling solution reduces the cutting temperature. Liu et al. [11] achieved a temperature reduction of 57.1 % using RHVT cooling compared to dry hard turning. Sarma and Dixit [12] found that at high cutting speeds dry turning compromises machined surface roughness due to rapid tool wear as opposed to RHVT cooling.

The main drawback of RHVT cooling is that there is no lubrication function while the main drawback of MQL is the poor cooling effect. Therefore, the researchers suggested combining them. Singh and Sharma [13] showed that when turning commercially pure titanium, the combination of MQL and RHVT compared to MQL alone decreases surface roughness at different combinations of cutting parameters. Deiab et al. [14] found that MQL with vegetable oil in combination with RHVT provides the lowest tool flank wear in turning titanium Ti-6Al-4V alloy compared to wet machining, dry machining, MQL with vegetable oil, RHVT cooling and cryogenic machining.

In order to obtain maximum cooling and lubrication effect, machining must be performed with optimal cutting parameters. Although the Taguchi method (TM) allows the study of multiple process responses simultaneously [15], it can only be used to optimize and evaluate the impact of each response individually (single criterion optimization). Sekulic et al. [16] found that TM is an efficient means of finding the optimal cutting parameters to reach minimum surface roughness or minimum main cutting force in high-pressure jet assisted turning of Inconel 718.

To solve multi-criteria optimization problems, TM can be used in combination with the grey relational analysis (GRA) first proposed by Deng [17]. GRA converts multi-criteria optimization problems into single criterion ones. It should be noted that there are fine differences with respect to combining, so that the grey based TM and Taguchi based GRA are distinguished. Thus, Puh et al. [18] used grey based TM, while Gupta and Sood [19] used Taguchi based GRA for multi-criteria optimization of turning. The accuracy and competence of prediction were confirmed for both methods.

In GRA different weight values are to be assigned to different criteria depending on their relative importance, which is completely left to the subjective decision-making of the researcher. This can be successfully overcome by applying the entropy measurement technique offered by Wen et al. [20]. Kumar et al. [21] tested entropy weighted grey based TM to optimize the cutting parameters for duplex turning of Inconel 718 by allocating the calculated entropy-weight to each criterion. Their results showed an improvement in the surface roughness, and primary and secondary cutting force in the optimal state.

There is also a lot of other literature available on optimizing cutting parameters in machining processes, including turning, milling and hybrid machining [22-25]. Some papers also discuss the cryogenic machining to reach the sustainability requirements [26, 27].

However, regarding the TM and grey based TM optimization of cutting parameters for turning martensitic stainless steels, only a few studies have been reported. The studies have focused on AISI 410, AISI 416 and AISI 440B workpiece materials and using of TiCN/Al_2O_3, Ti(C, N, B), (Ti, Al)N, ceramics and PcBN cutting tools in wet or dry machining conditions. The machining responses considered for single criterion or multi-criteria optimization problems were: surface roughness [28-34], tool wear [30, 32], machining time [34] and material removal rate [29, 34]. Furthermore, very few papers are available dealing with the combination of MQL and RHVT, and none deals with martensitic stainless steels. Therefore, the goal set here is to inspect the impact of emulsion cooling and MQL without and with the RHVT when turning martensitic stainless steel X20Cr13 and test the Taguchi based entropy weighted GRA for multi-criteria turning process optimization.

2. MATERIALS AND METHODS

2.1 Taguchi based entropy weighted grey relational analysis

Optimization using the Taguchi based entropy weighted GRA is explained in more detail below.

Step 1. *Designing experiments*

This step involves: identifying the machining process responses and cutting parameters for inspection, determining the levels for the cutting parameters, and selecting the proper Taguchi orthogonal array according to which the experiments will be performed.

Step 2. *Conducting experiments*

Step 3. *Normalization of responses*

The normalized experimental results according to the *lower-the-better* (L-T-B) criterion can be calculated as:

$$x_{ij} = \frac{\max y_{ij} - y_{ij}}{\max y_{ij} - \min y_{ij}}, \qquad i = 1, \dots n, \qquad j = 1, \dots, r \tag{1}$$

where y_{ij} are original data (the i^{th} experimental result for the j^{th} machining response). For the *higher-the-better* (H-T-B) criterion, the following expression can be used:

$$x_{ij} = \frac{y_{ij} - \min y_{ij}}{\max y_{ij} - \min y_{ij}}, \qquad i = 1, \dots, n, \qquad j = 1, \dots, r \tag{2}$$

Step 4. *Grey relational coefficients (GRCs) calculation*

GRCs can be determined as:

$$\xi_{ij} = \frac{\zeta}{1 - x_{ij} + \zeta}, \qquad i = 1, \dots, n, \qquad j = 1, \dots, r \tag{3}$$

The distinguishing coefficient ζ generally has a value of 0.5, i.e. $\zeta \in [0, 1]$. GRC determines how close the actual normalized experimental results x_{ij} are to the reference or the ideal target sequence $x_{0j} = 1$, and the larger the value of ξ_{ij}, the closer these two variables are.

Step 5. *Entropy weighting*

a) Sum of GRCs for each response

$$D_j = \sum_{i=1}^{n} \xi_{ij}, \qquad j = 1, \dots, r \tag{4}$$

b) Normalized coefficient

$$k = \frac{1}{(e^{0.5} - 1) \times n} = \frac{1}{0.6487 \times n} \tag{5}$$

c) Entropy of each response

$$e_j = k \sum_{i=1}^{n} w_e\left(\frac{\xi_{ij}}{D_j}\right), \qquad j = 1, \dots, r, \qquad w_e(x) = x e^{(1-x)} + (1 - x)e^{x} - 1 \tag{6}$$

d) Sum of entropy

$$E=\sum_{j=1}^{r} e_j \tag{7}$$

e) Weight of each response

$$w_j=\frac{1-e_j}{r-E}, \qquad \sum_{j=1}^{r} w_j=1 \tag{8}$$

Step 6. *Grey relational grades (GRGs) calculation*

GRGs can be evaluated as:

$$\Gamma_i=\sum_{j=1}^{r} w_j\, \xi_{ij}, \qquad i=1,\dots,n \tag{9}$$

Step 7. *Calculation of the Taguchi's signal-to-noise (S/N) ratio for GRGs*

The higher Γ_i, the corresponding response is closer to the ideal one. Hence, the *S/N* ratio for the *higher-the-better* (H-T-B) criterion should be used:

$$SN_i=-10\log\sum_{i=1}^{n}\frac{1}{\Gamma_i^2} \tag{10}$$

Step 8. *Analysis of experimental results*

Here, the optimum levels of cutting parameters are detected on the basis of an analysis of *S/N* ratios, and the significance of their influence is determined based on the analysis of the variance (ANOVA) of the *S/N* ratios.

Step 9. *Conducting of confirmation experiment*

Once the optimal solution for cutting parameters is identified, the last effort is prediction and verification of the improvements in the machining responses. The expression for predicting the *S/N* ratio is:

$$SN_{opt}=SN_t+\sum_{k=1}^{s}(SN_k-SN_t) \tag{11}$$

where SN_t is the total mean of *S/N* ratios, SN_k is the highest mean *S/N* ratio for the cutting parameter and s is the total number of cutting parameters with significant influence on the machining responses.

2.2 The experimental procedure

The material tested in the experiment was quenched and tempered martensitic stainless steel X20Cr13 (0.236 % C, 11.97 % Cr, 0.299 % Ni, 0.683 % Mn, 0.352 % Si, 0.125 % Mo, 0.023 % S, 0.044 % P, 0.053 % V, 0.07 % Nb, 0.195 % Cu, 85.85 % Fe). The mechanical properties were as follows: yield strength $R_{p(0.2)}$ = 750 MPa, tensile strength R_m = 881 MPa, and Brinell hardness = 272 HB.

The cutting speed v_c in m/min, feed f in mm/rev, depth of cut a_p in mm and cooling condition (emulsion cooling, MQL, and MQL+RHVT) were selected as cutting parameters. The average surface roughness *Ra* in μm, mean roughness depth *Rz* in μm, tool life *T* in min and material removal rate MRR = 1000 × v_c × f × a_p in mm^3/min are considered as response parameters. The levels of cutting parameters are presented in Table I. The tests were organized corresponding to Taguchi orthogonal array $L_{27}(3^4)$, Table II. The order in which the experiments were performed was the result of random selection using an Android-platform program Random Generator 5.0.1.

Table I: Levels of cutting parameters.

Parameter	**Level**		
	1	2	3
Cutting speed v_c (m/min)	260	290	320
Feed f (mm/rev)	0.3	0.35	0.4
Depth of cut a_p (mm)	1	1.5	2
Cooling method C	Emulsion	MQL	MQL+RHVT

Table II: Experimental layout for Taguchi orthogonal array $L_{27}(3^4)$.

Test order	**Test number**	**Parameters**						
		v_c	f	$v_c \times f$	a_p	$v_c \times a_p$	$f \times a_p$	C
11	1	1	1	1	1	1	1	1
20	2	1	1	1	2	2	2	2
5	3	1	1	1	3	3	3	3
1	4	1	2	2	1	1	2	2
19	5	1	2	2	2	2	3	3
23	6	1	2	2	3	3	1	1
14	7	1	3	3	1	1	3	3
26	8	1	3	3	2	2	1	1
3	9	1	3	3	3	3	2	2
21	10	2	1	2	1	2	1	2
27	11	2	1	2	2	3	2	3
6	12	2	1	2	3	1	3	1
2	13	2	2	3	1	2	2	3
4	14	2	2	3	2	3	3	1
12	15	2	2	3	3	1	1	2
16	16	2	3	1	1	2	3	1
22	17	2	3	1	2	3	1	2
25	18	2	3	1	3	1	2	3
9	19	3	1	3	1	3	1	3
10	20	3	1	3	2	1	2	1
15	21	3	1	3	3	2	3	2
17	22	3	2	1	1	3	2	1
7	23	3	2	1	2	1	3	2
24	24	3	2	1	3	2	1	3
18	25	3	3	2	1	3	3	2
13	26	3	3	2	2	1	1	3
8	27	3	3	2	3	2	2	1

The longitudinal turning experiments were conducted on the bars with a diameter of 80 mm and a length of 463 mm. CNC lathe TU 360 Prvomajska, Seco DNMG 150608-MF-4 cutting inserts of TM 4000 grade (tungsten carbide), and a tool holder DDJNL 2525M15-M were used.

In wet machining, 5 % emulsion (INA BU 7 concentrate) was employed. For MQL, the biodegradable oil LUB 200 was used.

The turning process in MQL and MQL+RHVC conditions is performed using an external unit VE1B-PB2_10 (manufactured by SKF) and a counter-flow vortex tube manufactured by EXAIR, model 3825 connected in one system. The system functions in such a way that the supply of compressed air at room temperature comes directly in front of the MQL unit where there are two ball valves that open/close the air flow to the MQL unit and RHVT, Fig. 1. In this way it is possible to apply either lubrication (MQL) or cooling (RHVT) or a combination thereof (MQL+RHVT). Also, a nozzle has been designed to allow micro-droplets from the MQL unit and chilled compressed air from the RHVT to be connected in one stream (single channel system) before entering the cutting zone, thus allowing for simultaneous lubrication and cooling. The nozzle model was printed using 3D Form 2 printer (manufactured by Formlabs), which operates on the principle of stereolithography using a laser device to obtain solid isotropic parts from a liquid photopolymer resin. The material of which the nozzle was made is a standard grey photoreactive resin, which is exquisite for capturing small details with high resolution and finishing and matte finish without the need for subsequent hardening.

The surface roughness measurements were made using a Hommel Tester T1000 profilometer (manufactured by JENOPTIK). To avoid possible mistakes due to re-clamping operation, the surface roughness parameters had been measured directly on the workpiece in the lathe. Also, to reduce deviation, the mean value of three measurements was adopted as a result of each experiment.

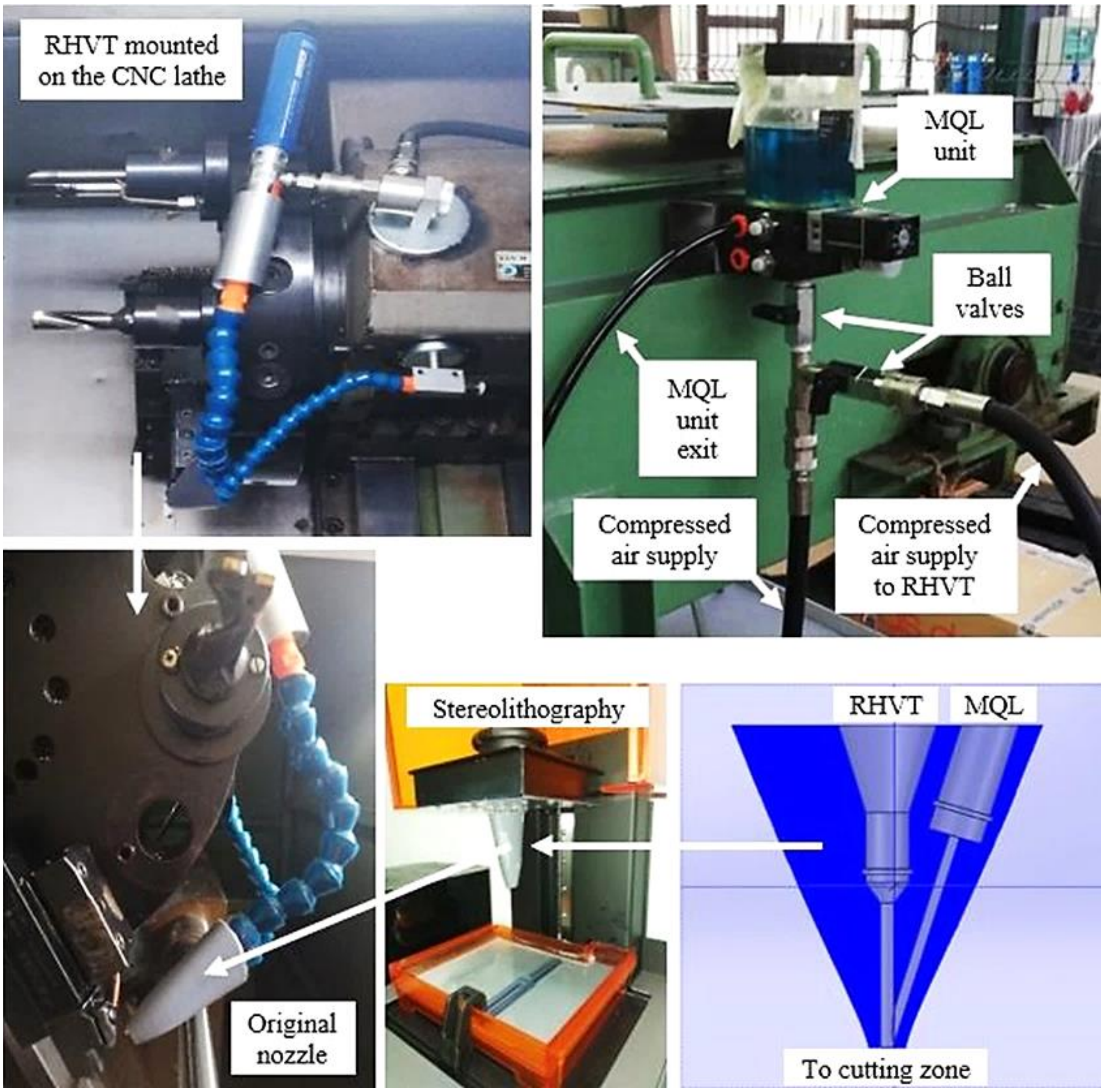

Figure 1: Set up of MQL unit, RHVT and MQL+RHVT with 3D printed original nozzle.

3. RESULTS AND DISCUSSION

3.1 Determination of the optimal cutting parameters

In this work, an optimum combination of cutting parameters for X20Cr13 martensitic stainless steel turning are obtained by using the Taguchi based entropy weighted GRA. The results and calculations are presented below.

Table III shows the experimental results and their normalized values. Also, grey relational coefficients, weight value for each machining response, rank and *S/N* ratio for each calculated GRG are presented in Table IV. The experiment under No. 3 has the best combination of cutting parameters among 27 performed experiments since it has the highest Γ_i value as depicted in Table IV.

The mean *S/N* ratios calculated from Table IV taking the average of the *S/N* ratios for each level of input cutting parameters individually, are presented in Table V. Besides, the total mean of the *S/N* ratios for all 27 tests is given too. The optimal levels for cutting parameters can easily be obtained from Table V. For any cutting parameter, the optimum level is one with the maximal value of mean *S/N* ratio. Therefore, the optimum combination is as follows: first level of cutting speed v_c, first level of feed *f*, third level of depth of cut a_p, and the MQL+RHVT cooling method. According to the results presented in Table V, the feed has the utmost influence on reducing the surface roughness parameters *Ra* and *Rz* and improving tool life *T* and material removal rate *MRR*, and then cooling method, depth of cut and cutting speed. However, the exact contribution steel needs to be found.

Table III: Experimental results and normalized values: ideal sequence (1, 1, 1, 1).

Test number	Responses				Normalized values			
	Ra (μm)	*Rz* (μm)	*T* (min)	*MRR* (mm^3/min)	*Ra* L-T-B	*Rz* L-T-B	*T* H-T-B	*MRR* H-T-B
1	1.587	8.10	18.7	78000	0.63744	0.74462	1.00000	0.00000
2	1.760	8.46	3.81	117000	0.38039	0.64785	0.17689	0.21910
3	1.343	7.15	5.35	156000	1.00000	1.00000	0.26202	0.43820
4	1.653	8.53	8.87	91000	0.53938	0.62903	0.45661	0.07303
5	1.678	8.08	6.05	136500	0.50223	0.75000	0.30072	0.32865
6	1.913	9.62	5.01	182000	0.15305	0.33602	0.24323	0.58427
7	1.727	8.80	9.50	104000	0.42942	0.55645	0.49143	0.14607
8	2.016	9.31	3.50	156000	0.00000	0.41935	0.15976	0.43820
9	1.921	9.72	0.76	208000	0.14116	0.30914	0.00829	0.73034
10	1.544	7.61	6.10	87000	0.70134	0.87634	0.30348	0.05056
11	1.442	7.34	3.41	130500	0.85290	0.94892	0.15478	0.29494
12	1.575	8.02	2.83	174000	0.65527	0.76613	0.12272	0.53933
13	1.592	8.06	5.05	152250	0.63001	0.75538	0.24544	0.41713
14	1.921	9.61	3.65	152250	0.14116	0.33871	0.16805	0.41713
15	1.953	9.42	0.99	203000	0.09361	0.38978	0.02101	0.70225
16	1.825	8.86	3.38	116000	0.28380	0.54032	0.15312	0.21348
17	1.916	9.67	1.05	174000	0.14859	0.32258	0.02432	0.53933
18	1.844	10.08	1.02	232000	0.25557	0.21237	0.02266	0.86517
19	1.594	7.84	5.58	96000	0.62704	0.81452	0.27474	0.10112
20	1.623	8.30	2.55	144000	0.58395	0.69086	0.10724	0.37079
21	1.739	8.18	0.81	192000	0.41159	0.72312	0.01106	0.64045
22	1.742	9.05	3.42	112000	0.40713	0.48925	0.15533	0.19101
23	1.669	7.82	0.61	168000	0.51560	0.81989	0.00000	0.50562
24	1.685	8.31	1.13	224000	0.49183	0.68817	0.02875	0.82022
25	1.898	8.68	1.11	128000	0.17533	0.58871	0.02764	0.28090
26	1.777	8.28	1.31	192000	0.35513	0.69624	0.03870	0.64045
27	2.007	10.87	0.85	256000	0.01337	0.00000	0.01327	1.00000

Table IV: Calculated grey relational grades.

Test number	**Grey relational coefficients**				**Grey relational grade**		
	Ra	*Rz*	*T*	*MRR*	*Γ*	Rank	*S/N* ratio H-T-B
1	0.57967	0.66192	1.00000	0.33333	0.64374	2	-3.82584
2	0.44658	0.58675	0.37790	0.39035	0.45039	18	-6.92824
3	1.00000	1.00000	0.40388	0.47090	0.71868	1	-2.86932
4	0.52049	0.57407	0.47921	0.35039	0.48104	15	-6.35642
5	0.50112	0.66667	0.41692	0.42686	0.50288	11	-5.97068
6	0.37121	0.42956	0.39784	0.54601	0.43616	21	-7.20714
7	0.46704	0.52991	0.49575	0.36929	0.46550	17	-6.64166
8	0.33333	0.46269	0.37307	0.47090	0.40999	26	-7.74443
9	0.36796	0.41986	0.33519	0.64964	0.44316	19	-7.06874
10	0.62605	0.80172	0.41788	0.34496	0.54764	4	-5.23010
11	0.77268	0.90732	0.37169	0.41492	0.61663	3	-4.19947
12	0.59191	0.68132	0.36303	0.52047	0.53917	6	-5.36543
13	0.57472	0.67148	0.39855	0.46174	0.52661	7	-5.57016
14	0.36796	0.43056	0.37539	0.46174	0.40891	27	-7.76744
15	0.35552	0.45036	0.33807	0.62676	0.44268	20	-7.07825
16	0.41112	0.52101	0.37123	0.38865	0.42300	23	-7.47328
17	0.36998	0.42466	0.33883	0.52047	0.41348	25	-7.67084
18	0.40179	0.38831	0.33845	0.78761	0.47904	16	-6.39252
19	0.57277	0.72941	0.40808	0.35743	0.51691	9	-5.73170
20	0.54582	0.61794	0.35900	0.44279	0.49138	14	-6.17165
21	0.45939	0.64360	0.33581	0.58170	0.50512	10	-5.93218
22	0.45751	0.49468	0.37184	0.38197	0.42650	22	-7.40166
23	0.50792	0.73518	0.33333	0.50282	0.51980	8	-5.68321
24	0.49595	0.61589	0.33985	0.73554	0.54680	5	-5.24341
25	0.37745	0.54867	0.33959	0.41014	0.41896	24	-7.55659
26	0.43673	0.62207	0.34216	0.58170	0.49566	13	-6.09634
27	0.33633	0.33333	0.33631	1.00000	0.50150	12	-5.99457
	Weights						
	0.249998	0.249969	0.250022	0.250011			

Table V: Response table (means) for *S/N* ratio.

Level	**Cutting parameters**			
	v_c	f	a_p	C
1	**-6.06805**	**-5.13933**	-6.19860	-6.55016
2	-6.30528	-6.47538	-6.47026	-6.61162
3	-6.20126	-6.95989	**-5.90573**	**-5.41281**
Max-Min	0.23722	1.82056	0.56453	1.19881
Rank	4	1	3	2
Total mean of *S/N* ratios = -6.19153				

3.2 Analysis of variance (ANOVA)

The aim of ANOVA is to identify the cutting parameters that notably influence the *S/N* ratio. Also, it can be used to resolve the contribution of the change of cutting parameter to the machining response. The degrees of freedom *DF*, sum of squares *SS*, mean squares *MS* (variance) and *F*-value (variance ratio) were calculated. Besides, for each parameter, the contribution *PC* in percentages was determined too. The results are presented in Table VI. The *PC* value shows the relative power of a parameter to decrease variation. The higher the *PC* value, the more important is the contribution of cutting parameter change. It can be seen that the feed influences the most (40.43 %), followed by cooling method (20.73 %). The latter is very important information from the aspect of machining sustainability. Furthermore, the cutting speed, depth of cut and two-factorial interactions had no statistically significance on the *S/N* ratios at the confidence level of 95 % because their *F*-calculated values are less than F_0-tabulated values, so they can be neglected.

Table VI: ANOVA for *S/N* ratio.

	DF	***SS***	***MS***	***F***	***PC*** (%)
v_c	2	0.25451	0.12726	0.20*	0.64
f	2	16.00261	8.00131	12.89	40.43
a_p	2	1.43479	0.71739	1.16*	3.62
C	2	8.20351	4.10176	6.61	20.73
$v_c \times f$	4	4.38894	1.09723	1.77*	11.09
$v_c \times a_p$	4	4.14836	1.03709	1.67*	10.48
$f \times a_p$	4	1.42385	0.35596	0.57*	3.60
Error	6	3.72543	0.62091		9.41
Total	26	39.58201			

F_0-tabulated for $\alpha = 0,05$: $F_0 = F_{(2,\,6)} = 5.14$ and $F_0 = F_{(4,\,6)} = 4.53$; *not significant

3.3 Confirmation experiment

Machining responses for initial and optimum setting of cutting parameters are compared in Table VII. The initial setting captures first level of cutting speed v_c, second level of feed *f*, first level of depth of cut a_p, and MQL, which is the fourth experiment in the $L_{27}(3^4)$ Taguchi experimental design. According to the analysis, the optimal solution regarded as a confirmation experiment capture first level of cutting speed v_c, first level of feed *f*, third level of depth of cut a_p, and MQL+RHVT cooling method. As shown in Table VII, the average surface roughness *Ra* is improved from 1.653 μm to 1.343 μm, mean roughness depth *Rz* is improved from 8.53 μm to 7.15 μm and material removal rate *MRR* is increased from 91000 mm^3/min to 156000 mm^3/min, however the tool life *T* is declined from 8.87 min to 5.35 min.

Table VII: Confirmation experiment results.

Parameters	**Initial setting**	**Optimal setting**		**Improvement**
		Prediction	Experiment	
Setting level	$v_{c1}\,f_2\,a_{p1}\,C_2$	$v_{c1}\,f_1\,a_{p3}\,C_3$	$v_{c1}\,f_1\,a_{p3}\,C_3$	
Ra (μm)	1.653		1.343	18.75 %
Rz (μm)	8.53		7.15	16.18 %
T (min)	8.87		5.35	-39.68 %
MRR (mm^3/min)	91000		156000	71.43 %
S/N ratio	-6.35642	-4.36061	-2.86932	54.86 %

4. CONCLUSION

The cutting parameters multi-criteria optimization for the turning of X20Cr13 martensitic stainless steel was carried out. ANOVA showed that the feed and cooling method are the dominant cutting parameters contributing the most to the concurrent minimizing of surface roughness and tool life while maximizing material removal rate. On the subject of the multi-criteria optimization problem, it should be pointed out that the Taguchi based entropy weighted GRA is very easy to grasp for practical use in any machine shop.

Furthermore, the combination of MQL with RHVT proved to be the best cooling method. It can be utilized as an efficient alternative to wet machining and MQL alone. Therefore, the use of classic MWFs (i.e. emulsions), when turning martensitic stainless steels, can be excluded. The transition from oil-based MWFs to MQL+RHVT cooling method is a step forward towards sustainable machining, resulting in a significant decrease in the ecological load and in the risk of danger to human health.

Finally, for better understanding and more comprehensive optimization of aforementioned cooling method, it would be of further interest to establish the mathematical models between the machining responses and cutting speed, feed and depth of cut.

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