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Optimization of Cutting Parameters, Condition and Geometry in Turning AISI 316L Stainless Steel Using the Grey-Based Taguchi Method

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In this study, experimental optimization of cutting forces, surface roughness and the hardness of material after turning of AISI 316L stainless steel, using conventional and wiper insert cutting tools under dry, CO_2 and MQL cutting conditions, is presented. The influences of feed rate, cutting depth, and cooling system on surface roughness, cutting force and material hardness were examined. In order to optimize the turning process, Grey relational analysis optimization method was used. The optimal machinability parameters of AISI 316L stainless steel with coated carbide insert were successfully determined.

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1. Introduction

The steel materials used in the manufacturing industry are becoming more advanced day by day. Stainless steel, is commonly used in a wide range of applications in the manufacturing sector, due to its high mechanical properties, corrosion resistance and low thermal conductivity [1]. Although it is more expensive, compared to other forms of steel, stainless steel is becoming increasingly popular for use in many fields, ranging from food to health, chemistry to electronics, from defense industry to nuclear power plants and automotive to aerospace, due to its superior mechanical properties and unique corrosion resistance [2–4]. Stainless steel is a type of steel which contains 11–18% of chromium in its composition [5].

Austenitic and ferritic stainless steel is used particularly in machinery and manufacturing industry. These forms of steel fall under the "difficult to machine" materials class with their low thermal conductivity properties. Low thermal conductivity, leads to high shear force, high cutting temperatures, rapid tool wear, produces difficult to break chips, causes chips to bond to the cutting edge and leads to poor surface quality [6]. In addition the energy used for plastic deformation of the workpiece during machine turning is converted to heat and it is well known that heat mostly occurs in the primary deformation zone. However, heat generated during deformation is closely associated with friction and shear force in the tool-chip interface, which vary according to tool geometry and cutting parameters. Tool-chip contact length and therefore tool geometry directly affect tool life and machining efficiency [7].

In recent years, it is possible to come across many experimental studies investigating the effects of cutting parameters on shear force and surface roughness, occurring during machining of various forms of stainless steel. In one of these studies, the machinability of AISI 304 and AISI 316 stainless steel with coated cemented carbide cutting tools was investigated and cutting speed was reported as an important parameter for surface roughness *Ra* [8]. In another study, the F_c generated during the turning of AISI 304 austenitic stainless steel with TIC-coated cutting tool, was theoretically and experimentally evaluated and it was indicated that the theoretical approach could be used with 80% average accuracy [9]. *Ra* is reported to decrease parallel to the decrease in cutting sound pressure level during the turning of AISI 304 stainless steel at low feed rate and high cutting speeds [10, 11]. In another study, the verification tests conducted according to the optimum cutting parameters for surface roughness and cutting force during turning of austenitic stainless steel, resulted in a 23.4% improvement [12]. A variance analysis on the *Ra* resulting from the machining of AISI 304 stainless steel, revealed that feed rate had a 51.84% effect on Ra [13].

Time, volume and efficiency of production are not the only factors that should be taken into consideration in the assessment of success of a production method. Other important considerations must include the effect on the environment and human health. Machine turning applications, which use cooling techniques that respect human health and the environment, have been developed. The performance characteristics of the alternative cooling technique were found to be superior to the conventional cooling techniques [1, 3-22]. The MQL technique which delivers reduced tool wear and improved surface quality thanks to a reduction in the heat generated in the tool-chip and workpiece-chip cutting zone are important results [23]. Liquid nitrogen, and carbon dioxide are also used as alternative cooling systems for the cooling of the cutting zone. A 55% reduction in edge wear was reported following the use of liquid nitrogen cooling [24].

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In this study; the effect of feed rate, depth of cut and cooling system on surface roughness and cutting force during machine turning of AISI 316L stainless steel is investigated. Taguchi Grey analysis technique was used in the optimization of the turning process. Furthermore, variance analysis was conducted to determine the effect of each parameter on the results. As a result of this analysis, the effect of feed rate, depth of cut and cooling system on surface roughness and cutting force during machine turning of AISI 316L stainless steel was determined.

2. Materials and methods

AISI 316L was used for the purposes of this study. The experiment samples were rod-shaped, 130 mm in length and 25 mm in diameter. During the machining process, CNMG 12 04 08 mm cutting tips, produced by Sandvik company were used. The Johnford TC 35 CNC Fanuc OT, an x-z axis CNC machine was used during the experiment. A perhometer M1 type surface roughness meter, manufactured by Mahr was used in the experiment. Surface roughness can be determined with various parameters according to DIN, ISO, JIN, AISI standards. A KISTLER 9121 dynamometer with KISTLER 5019b type load amplifier and the DynoWare analysis software was used for power measurement during the experiments (Fig. 1).

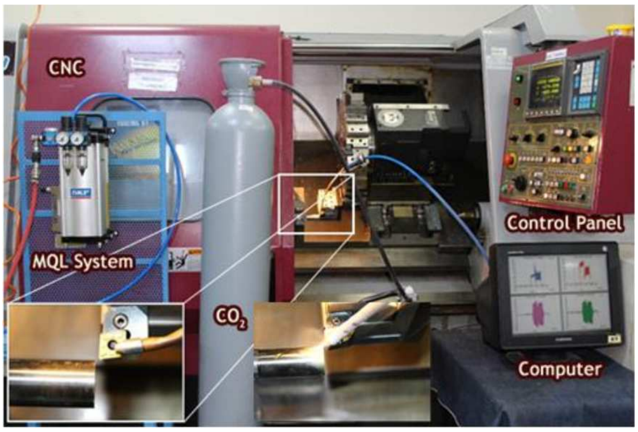

Fig. 1. The experimental setup.

TABLE I

Factors and designated levels.

Factors	Level 1	Level 2	Level 3
Feed rate [mm/rev]	0.1	0.2	0.3
Depth of cut [mm]	0.5	1	1.5
Cooling system	Dry	MQL	CO_2

Three levels were set between 0.1 to 0.3 mm/rev for the feed rate parameter, and 0.5 and 1.5 mm for depth of cut. Dry, MQL (minimum quantity lubrication) and CO_2 options were examined for the cooling system factor. Table I shows key factors and designated levels, affecting cutting force and surface roughness.

2.1. Taguchi design

Taguchi parametric design is a very effective design tool, offering simple and systematic qualitative optimal design at a relatively low cost. It has become very popular in the last two decades. By helping to determine the significant factors, this approach not only saves the experimental time but also the costs. Selection of an orthogonal array is one of the most important steps involved in Taguchi technique. An orthogonal array is a small set of all the possibilities, which helps to determine the least number of experiments. It will further help to conduct experiments to determine the optimum level for each process parameter and to establish the relative importance of individual process parameters [25]. For the experiments performed according to Taguchi L_9 orthogonal array, levels of the set of parameters are given in Table II.

TABLE II

The orthogonal array L_9-based surface roughness and cutting force.

Exp. no.	Variables	Surface roughness, [μm] (FF)	Surface roughness, [μm] (FW)	Cutting force [N] (FF)	Cutting force [N] (FW)
1	$A_1B_1C_1$	0.618	0.532	127.861	209.621
2	$A_1B_2C_2$	0.406	0.883	235.389	305
3	$A_1B_3C_3$	0.641	1.139	394.356	417.966
4	$A_2B_1C_2$	1.519	0.739	213.403	100.229
5	$A_2B_2C_3$	1.493	0.562	680.935	736.619
6	$A_2B_3C_1$	1.449	1.402	559.572	659.523
7	$A_3B_1C_3$	3.457	0.588	301.659	543.746
8	$A_3B_2C_1$	3.694	0.967	523.654	753.211
9	$A_3B_3C_2$	3.380	0.776	708.567	701.455

2.2. Taguchi-based Grey relational analysis method

The obtained experimental results and the determined parameters were optimized with Grey-based Taguchi method. Using regression model, researches were carried out calculating an equation between dependent parameters and independent parameters. The Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only.

Experimental design was done using Taguchi method. Hence, it has been possible to reach more comprehensive results with doing less experiment. In this sense, time and money have been used more efficiently [26, 27]. While a single outcome is optimized in the Taguchi method, multiple outcomes can be optimized in a Grey relational analysis [28]. In this study, Taguchi method was used in the experimental design step, Grey relational analysis method was used in the optimization step.

Grey relational analysis optimization process was carried out in the following three steps [28].

1. Normalization of experimental results (the lowest–the best).
2. Calculation the Grey relational coefficient.
3. Calculation of the Grey relational degree.
4. Determination of optimal experiment parameters.

In the normalization step, the experimental results were normalized using the following equation according to "the lowest–the best" principle.

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)}, \tag{1}$$

where, $x_i(k)$ refers to the value at the ith series and kth row after normalization process, $\min y_i(k)$ refers to the minimum value of the ith series, $\max y_i(k)$ refers to the maximum value of the ith series and $y_i(k)$ refers to the original value of the i series at kth row.

In step two, Grey relational coefficient was calculated via Eq. (2)

$$\xi_i(k) = \frac{\Delta \min + \zeta \Delta \max}{\Delta 0_i(k) + \zeta \Delta \max}. \tag{2}$$

Here, ζ is a distinguishing coefficient between 0 and 1, $\Delta 0_i$ is the amount of deviation between the reference series and the normalization values. $\Delta \min$ refers to the minimum value of the deviation sequence from the reference series and $\Delta \max$ refers to the maximum value of deviation sequence from the reference series.

In the step three, Grey relational degree was calculated by Eq. (3)

$$\gamma_i = \frac{1}{n} \sum_{k-1}^{n} \xi_i(k). \tag{3}$$

3. Results and discussion

Influence of the cutting parameters and the effect of cutting geometry and parameters on surface roughness *Ra* and cutting force on turning of a AISI 316L stainless steel with Sandvik CNMG 12 04 08 conventional (FF) and wiper (FW) inserts is discussed in this section.

3.1. Optimization of experimental results for surface roughness and cutting force

Values of surface roughness and cutting force obtained in the experimental step, for Taguchi L_9 experiment design, are shown in Table II. Grey relational analysis method was applied to the experimental results, as shown in Table III and the other steps (normalization, delta values, and Grey relational grade) results are given in Table IV and Table V.

TABLE III

Normalized data, delta values and Grey relational grade for conventional insert tool.

Exp. no.	Cutting force [N]	Surface roughness [μm]	Normalized data		Delta values		Grey relational grade	
			Cutting force	Surface roughness	Cutting force	Surface roughness	values	rank
1	127.861	0.618	1.000	0.907	0.000	0.093	0.922	1
2	235.389	0.406	0.806	1.000	0.194	0.000	0.860	2
3	394.356	0.641	0.518	0.897	0.482	0.103	0.669	4
4	213.403	1.519	0.845	0.514	0.155	0.486	0.635	3
5	680.935	1.493	0.000	0.525	1.000	0.475	0.423	6
6	559.572	1.449	0.219	0.544	0.781	0.456	0.457	7
7	301.659	3.457	0.686	0.104	0.314	0.896	0.486	5
8	523.654	3.694	0.284	0.000	0.716	1.000	0.372	8
9	708.567	3.380	0.077	0.137	0.923	0.863	0.359	9

TABLE IV

Normalized data, delta values and Grey relational grade for wiper insert tool.

Exp. no.	Cutting force [N]	Surface roughness [μm]	Normalized data		Delta values		Grey relational grade	
			Cutting force	Surface roughness	Cutting force	Surface roughness	values	rank
1	209.621	0.532	0.832	1.000	0.168	0.000	0.875	1
2	305	0.883	0.686	0.597	0.314	0.403	0.584	2
3	417.966	1.139	0.513	0.302	0.487	0.698	0.462	3
4	100.229	0.739	1.000	0.762	0.000	0.238	0.839	4
5	736.619	0.562	0.025	0.966	0.975	0.034	0.637	5
6	659.523	1.402	0.143	0.000	0.857	1.000	0.351	6
7	543.746	0.588	0.321	0.936	0.679	0.064	0.655	7
8	753.211	0.967	0.000	0.500	1.000	0.500	0.417	8
9	701.455	0.776	0.079	0.720	0.921	0.280	0.496	9

The Grey relational coefficients were calculated using Eq. 2 and results are shown in Table V.

TABLE V

Grey relational degrees of the factor levels for conventional insert tool.

Levels	(A) Feed rate [mm/rev]	(B) Depth of cut [mm]	(C) Cooling system
Level 1	0.817	0.681	0.584
Level 2	0.505	0.552	0.618
Level 3	0.406	0.495	0.526

The Grey relational degrees related to each experimental result were calculated and the experimental results were ranked in order from highest Grey relational degree and are presented in Fig. 2, Table V and VI.

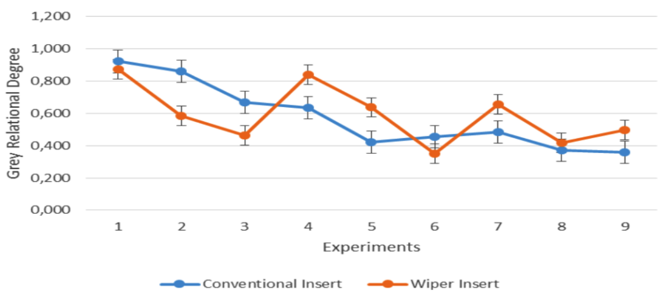

Fig. 2. Grey relational degrees for each experiment.

TABLE VI

Grey relational degrees of the factor levels for wiper insert tool.

Levels	(A) Feed rate [mm/rev]	(B) Depth of cut [mm]	(C) Cooling system
Level 1	0.640	0.789	0.547
Level 2	0.609	0.546	0.640
Level 3	0.523	0.436	0.585

As seen from the Table V and VI, A1 (feed rate: 0.1 mm/rev), B1 (depth of cut: 0.5 mm), and C2 (MQL) were selected as the optimal parameter levels. The optimal parameters levels will represent the lowest surface roughness and cutting force value.

4. Conclusions

This study of the machinability of AISI 316L stainless steel alloy material with SANDVIK CNMG 12 04 08 coated conventional (FF) and wiper (FW) inserts has produced useful results. The considered criteria for the machinability were surface roughness, cutting force and material hardness. Three control factors, which were considered to be effective in creating the most suitable conditions for the criteria (feed rate, depth of cut and corner radius) were chosen at three different levels and applied in the experimental study. Below is the summary of the results:

- Based on the Grey relational analysis, the optimal cutting parameters were A1B1C2 for surface roughness and cutting force, i.e. feed rate of 0.1 mm/rev, depth of cut of 0.5 mm and MQL cooling system.
- Taguchi method is beneficial for the experimental design of the machinability of AISI 316L stainless steel alloy. Having optimized the parameters is also fruitful for keeping the response values at required levels.
- Test results prove the effectiveness of the wiper inserts in providing excellent surface roughness. The results also suggest that the use of the wiper insert is an effective way, which significantly increases cutting efficiency, without changing the machined surface roughness in high feed turning operations.

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