

Evaluation of Cutting Parameters by Determination of the Grey Correlation Analysis Methods of the Effects on the Cutting Force and Surface Roughness of Duplex Stainless Steels (2205)

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Abstract: In this study, the effects of coated (TiAlN and TiN) drills and cutting parameters on drilling performance were investigated. Drilling operations were carried out by drilling holes 20 mm deep with 5 mm diameter drills on duplex stainless steel (2205). Three different cutting speeds (15, 20 and 25 m/min) and three different feed rates (0.05, 0.075 and 0.1 mm/min) were used in the experiments. The effects of different drills and cutting parameters on the cutting force and surface roughness are measured. Experiments were made in full factorial and optimum conditions were determined for the values measured by the gray relational analysis method. According to the gray correlation analysis value, it was found that the feed rates on the cutting force and surface roughness had a greater effect than the other factors. In addition, variance analysis (ANOVA) was performed to determine the effects of cutting parameters on cutting force (F_c) and surface roughness (R_a). According to ANOVA results, it is determined that the most effective parameter on R_a is the feed rate and the most effective parameter on the second degree is the cutting speed.

Keywords: cutting force; drilling; duplex stainless steel (2205); gray relational analysis; surface roughness

1 INTRODUCTION

Duplex stainless steels which are a new type of stainless steels have become considerably significant in the last couple of years. Duplex stainless steels consisting of ferrite and austenite mean "consisting of two pieces" in Latin. Existence of austenite provides ductility and general corrosion resistance whereas ferrite provides mechanical strength and resistance to stress corrosion cracking. Small amounts of sulphur (S) and phosphorous (P) are added into material to get rid of thermal cracking that can be formed during solidification of the structure. Ferritic stainless steels have high stress corrosion resistance and austenitic steels have the ability of high ductility, toughness and welding. Duplex stainless steels have the characteristics of these two structures (ferritic + austenitic). Duplex stainless steels, due to their high mechanical properties, enable the usage of parts with thinner section [1]. Duplex stainless steels contain austenite and ferrite phases in equal amounts. They are now widely used in many fields due to their outstanding mechanical properties and corrosion resistance [2-3].

In general, stainless steels, because of their high hardness values, toughness and lower thermal conductivities, are among the hardly machined materials [4-8]. Another problem in the machining of stainless steels is due to fracture toughness; because of these, the tool/chip interface temperatures increase affecting the surface quality adversely. Furthermore, at high cutting speeds, piling (BUE) is observed on the cutting edges and this spoils the quality of machined surface and increases the cutting forces [9]. Duplex stainless steels, even if they have better mechanical properties, they are hardly machined compared to austenitic stainless steels. This is due to the high strength of the alloy [10].

In drilling processes, determination of suitable cutting conditions is an important point. Because of the increasing demands in the manufacturing sector, investigation of the parameters affecting the wearing and life of cutting tools has always been a subject of research and the main target was to reach the optimum machining conditions by

decreasing the cost and increasing the performance [11]. To put forward the conditions with which the best results could be obtained, primarily the characteristic specifying the performance was determined and the factors affecting this characteristic were examined. Afterwards, tests were carried out to determine the effects of these factors on the characteristic specifying the performance and to find out the most suitable combination. In order to evaluate the effects and suitability of the machining parameters and factors, some techniques were developed to estimate the life of cutting tools before making tests. The most important advantages of these estimation techniques having experimental design, modelling and optimization are high accuracy, reliability and low cost. When the industrial conditions are considered, application of test design procedures is the most efficient approach to realize these tests most efficiently according to both economic conditions and time constraints and to commentate the results [12].

Grey system theory is an alternative and effective approach in cases of little or discrete information, much data and uncertainty. Grey theory is advised in cases which do not suit any distribution with multi variable statistics, have no sufficient data and which cannot be modelled due to uncertainty [13]. Grey relational analysis is getting widely used in literature as the decision making method. The applications of GRA in different fields give a better idea for the applicability of the method [14].

There are some studies investigating the machinability of duplex stainless steel alloys. Nomani et al., in their study, examined the effects on tool wear in the drilling of duplex stainless steels and austenitic stainless steels. In the study austenitic stainless steels gave better results [15]. Philip Selvaraj et al., in their study optimized the surface roughness, cutting forces and tool wear in the turning of duplex stainless steels with Taguchi method. In the study they determined that the effective parameter on surface roughness was feed rate and the most effective parameters on the main cutting forces were feed rate and cutting speed [16]. Paro et al., in their study, observed the tool wears created during drilling of duplex stainless steels with

internal cooled tools. For this process they used two different duplex stainless steels (Duploks 27 and A890 1). As a result, both of the steels were subjected to BUE. A890 1A was subjected more than the other. During machining of A890 1A tool life was observed to be higher [17]. Carlborg used four duplex and one high-alloy austenitic steels to compare the performance of cementite carbide tools. They investigated the tool life and tool wear [18]. Grzegory et al., in their study examined the effects of cutting parameters on the tool life during machining of duplex stainless steels with coated and uncoated carbide tools and they observed that tool life decreased with the increasing cutting speed. It was also observed that coated tools gave better results from the point of life [19]. Braham-Bouchnak et al., examined the tool wear during machining of duplex stainless steels by cooling with high pressure water and obtained better surfaces in the high pressure machining compared to dry cutting. At the same time, tool life increased 20% with the pressurized cooling [20].

Researches on duplex stainless steels are limited in number. Besides, most of the studies are on turning and milling. In this study, the effect of cutting parameters on cutting forces and surface form characteristics during drilling of duplex stainless steels was investigated by using grey analysis method. Besides, ANOVA variance analysis was used to determine the most effective parameter.

2 MATERIAL AND METHOD

2.1 Experimental Procedure

In the study, duplex 2205 quality stainless steel was taken as the test material. Chemical compositions of the test material duplex 2205 quality stainless steel are given in Tab. 1. In the tests TiN and TiAlN coated carbide drills (Walter cutting tool company) with 5mm diameter were used. The cutting forces and moment values were realized by using KISTLER 9272A dynamometer with 4 components. A multi-channel amplifier was used for transferring the signals coming from the dynamometer to the data reading card (KISTLER PCIM DAS 1602/16) and

finally KISTLER Dynoware 2825-A-02-01 software (compatible with Windows operating system) was employed to carry out the data processing and to obtain graphs. During processing, roughness values of hole surfaces were obtained by using portable Mahr Perthometer M1 type surface roughness measuring device, Figs. 1 and 2. In the drill ability tests three different feeds (0.05, 0.075 and 0.1 mm/rev) and three different cutting speeds (15, 20 and 25 m/min) were used. Tests were carried out at 20 mm depth by employing external cooling procedure. Tests were made by considering the catalogue values of the company (producing cutting tools with respect to ISO 3685) and using the values given in Tab. 2. In every test a new tip was used.

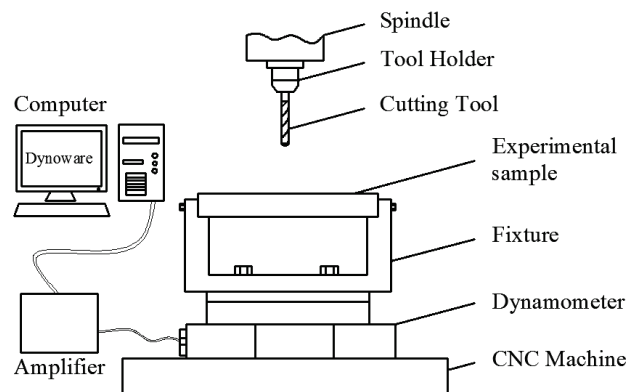


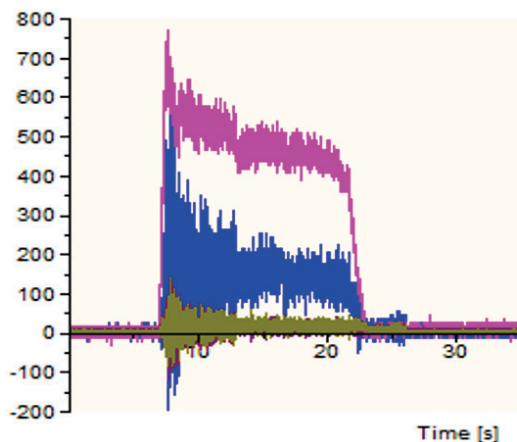
Figure 1 Schematic Diagram of Experimental Setup

Table 1 Chemical composition of Duplex Stainless Steel (2205)

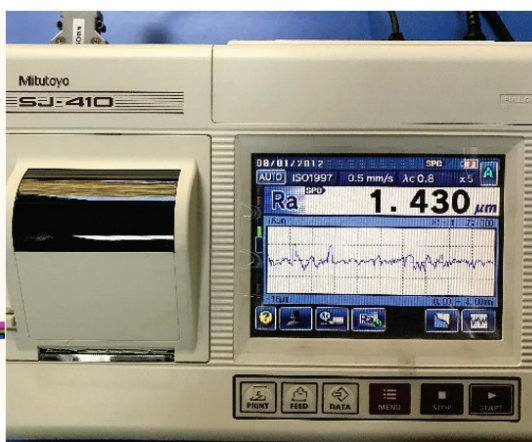
C	Mn	P	S	Si	Cr	Mo	Ni
0.03	2.0	0.035	0.015	1.0	21-23	2.5-3.5	4.5-6.5

Table 2 Cutting parameters and their levels

Symbol	Cutting Parameters	Level 1	Level 2	Level 3
A	Cutting tool coating types	TiAlN	TiN	-
B	Feed rate, <i>f</i> mm/rev	0.05	0.75	0.1
C	Cutting speed, <i>V</i> m/min	15	20	25



a)



b)

Figure 2 Measurements of Experimental Results. a) Cutting forces diagram; b) surface roughness

2.2 Plan of Experiment Analysis

In the last years Taguchi method is being used very often to increase the productivity in the research and

development made for the production of high quality products with low cost. The parameter design of Taguchi is very important for a keen design. Taguchi method is a special procedure developed to examine all of the

parameters that are planned to realize the tests with a limited number of tests [21-23]. For the application of Taguchi test plan 3-levelled two parameters and 2-levelled one parameter were used. Taguchi L18 orthogonal series was used to identify the degree of freedom condition necessary for the study. The parameters and their levels used in this series are given in Tab. 2. In the experimental studies the holes were drilled three times and averages were taken. Test design and corresponding test results are given in Tab. 3.

Table 3 Experimental design using Taguchi L18 orthogonal array and experimental results.

Experiment number	Cutting Parameters			Experimental Result	
	A	B	C	Ra / μm	Fc / N
1	1	1	1	1.21	496.42
2	1	1	2	1.11	491.71
3	1	1	3	0.97	486.33
4	1	2	1	1.43	576.84
5	1	2	2	1.17	519.39
6	1	2	3	0.89	498.34
7	1	3	1	1.69	758.09
8	1	3	2	1.42	694.59
9	1	3	3	0.99	714.05
10	2	1	1	0.99	555.96
11	2	1	2	0.76	515.77
12	2	1	3	0.59	483.82
13	2	2	1	1.17	663.14
14	2	2	2	1.07	642.21
15	2	2	3	0.82	624.06
16	2	3	1	1.93	740.39
17	2	3	2	1.67	664.07
18	2	3	3	1.03	700.16

3 DETERMINATION OF MACHINING PARAMETERS

3.1 Grey Relational Analysis (GRA)

The purpose of this study is to determine the optimum cutting parameters in drilling of the Duplex stainless steels with GRA method. The whole data was measured experimentally and was normalized in between 0-1. The most important point in the normalization of factor series is the type of approach which is to be used. As an example if the points in the series are wanted to be bigger values, points having bigger values in the linear normalization get values close to "1" and points having small values will get values close to "0" [24-26]. Normalization of the test results can be made with the following three different approaches;

If "the lowest the best" is the case then the series is normalized in the following way:

$$y_i(k) = \frac{\max x_i^0 - x_i^0(k)}{\max x_i^0 - \min x_i^0(k)} \tag{1}$$

Here, $y_i(k)$ GRA normalizing value, the maximum value of $x_i^0(k)$ is $\max x_i^0(k)$, the minimum value is $\min x_i^0(k)$. x^0 represents the optimum value. In the Grey relational analysis method, grey indicates the relational degree and relational degrees of eighteen series ($y_0(k)$ and $y_i(k)$, $i = 1, 2, \dots, 18$; $k = 1, 2, 3$) are determined. Grey relational coefficient $\xi_i(k)$ is calculated according to the equation 2-5 given below:

$$\xi_i(k) = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_{0i}(k) + \zeta \Delta_{\max}} \tag{2}$$

$$\Delta_{0i(k)} = \|y_0(k) - y_i(k)\| \tag{3}$$

$$\Delta_{\max} = \max_{\forall j \in i} \max_{\forall k} \|y_0(k) - y_i(k)\| \tag{4}$$

$$\Delta_{\min} = \min_{\forall j \in i} \min_{\forall k} \|y_0(k) - y_i(k)\| \tag{5}$$

Here, $\Delta_{0i}(k)$ is the absolute deviation value between $y_0(k)$ and $y_i(k)$, $\zeta =$ distinguishing coefficient (0_1); Δ_{\min} is the minimum value of Δ_{0i} , Δ_{\max} is the maximum value. Grey relational degree (γ_i) is obtained by taking the average of grey relational coefficients and is stated as follows:

$$\gamma_i = \frac{1}{n} \sum_{k=1}^n \xi_i(k) \tag{6}$$

Here n is the grey relational coefficient number obtained from the normalized test results. The High Gray association level indicates a strong association between $y_0(k)$ and $y_i(k)$. If the two series in comparison have the same values, grey relational degree is 1. Grey relational degree specifies how close the comparison series value is to the reference series value.

Sequences for the absolute deviation values calculated corresponding to normalized values, calculated grey relational coefficient and grey relational degree and 18 comparability series are given in Tab. 4 and Fig. 3.

Table 4 The sequences after data preprocessing, the calculated Grey relational coefficient and Grey relational grade for 18 comparability sequences

Experiment number	Calculated absolute deviation values		Calculated gray relational coefficient		Grey relational grade	Order
	Ra / μm	Fc / N	Measured Ra / μm	Measured Fc / N		
1	0.537313	0.95406	0.51938	0.915851	0.718	6
2	0.61194	0.971233	0.563025	0.945596	0.754	5
3	0.716418	0.990848	0.638095	0.982026	0.810	2
4	0.373134	0.660845	0.443709	0.595838	0.520	11
5	0.567164	0.87031	0.536	0.794042	0.665	7
6	0.776119	0.947059	0.690722	0.904256	0.797	4
7	0.179104	0	0.378531	0.333333	0.356	17
8	0.380597	0.231524	0.446667	0.394174	0.420	15
9	0.701493	0.160572	0.626168	0.373294	0.500	12
10	0.701493	0.736975	0.626168	0.655286	0.641	8
11	0.873134	0.883509	0.797619	0.811042	0.804	3
12	1	1	1	1	1.000	1
13	0.567164	0.346192	0.536	0.433348	0.485	14

Table 4 The sequences after data preprocessing, the calculated Grey relational coefficient and Grey relational grade for 18 comparability sequences (continuation)

Experiment number	Calculated absolute deviation values		Calculated gray relational coefficient		Grey relational grade	Order
	$Ra / \mu m$	F_c / N	Measured $Ra / \mu m$	Measured F_c / N		
14	0.641791	0.422503	0.582609	0.464039	0.523	10
15	0.828358	0.488679	0.744444	0.494403	0.619	9
16	0	0.064535	0.333333	0.348319	0.341	18
17	0.19403	0.342801	0.382857	0.432078	0.407	16
18	0.671642	0.211215	0.603604	0.387962	0.496	13

3.2 Analysis of Variance (ANOVA)

Variance Analysis (ANOVA) is one of the analysis methods used in investigating the effect of different parameters on the result. ANOVA provides the determination of the percentage contribution value of parameters affecting the output value. Percentage contribution (PCR) is calculated as follows:

$$PCR = \left(\frac{SS_A - (V_e) \cdot (\mathcal{G}_a)}{SS_T} \right) \times 100 \quad (7)$$

Here SS_A , Sum of squares for parameter A ; V_e , error variance; SS_T , sum of squares; \mathcal{G}_a , the degrees of freedom for parameters A and SS_T .

In addition to PCR , F -test can be used to analyse the effects of performance parameters. In general, the parameter with a high F value must have a great effect on the performance. An evaluation based on both PCR and F -test can be used to determine the most effective test parameter.

3.3. Analysis of Experimental Results

3.3.1 Grey Relational Analysis of Cutting Force and Surface Roughness

According to L18 experimental design results, surface roughness and main cutting force values are wanted to be lower. For this reason "the lowest-the best" sequence normalization approach was used. Absolute deviation values which were calculated against the normalized values of all of the measurement results and calculated grey relational analysis results are given in Tab. 4. For all of the tests, grey relational coefficients and then grey relational degrees were obtained. When the coefficients were found out, the distinguishing coefficient was taken as $\zeta = 0.5$. From Tab. 4 and Fig. 3 it is clearly seen that the lowest grey relational degree was obtained in the test no 12.

Table 5 Response table for machining parameters

Symbol	Parameter	Average grey relational grade by factor level			
		Level 1	Level 2	Level 3	Max-Min
A	Tool	0.6156*	0.5907		0.025
B	Feed rate	0.7878*	0.6016	0.4200	0.368
C	Cutting speed	0.5099	0.5958	0.7037*	0.194

First of all, for each parameter the same level values were summed and then their averages were taken and this way mean grey relational degree was obtained for that parameter. This process was repeated for each parameter in the second and third levels and the reaction table was obtained for grey relational degrees. As a result of the evaluation with respect to ("the lowest-the best") the results in Tab. 5 and Fig. 4 were obtained. According to Tab. 5, $A1B1C3$ was determined as the optimum parameter. It is

seen that the best result is $A1$; in the TiAlN coated tool, $B1$; at the 0.05 mm/rev feed rate and $C3$; at 25 m/min cutting speed.

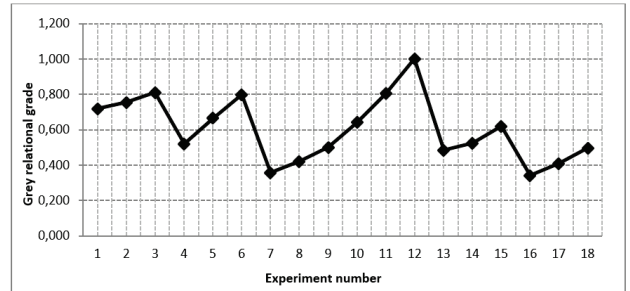


Figure 3 Grey relational grade graphic

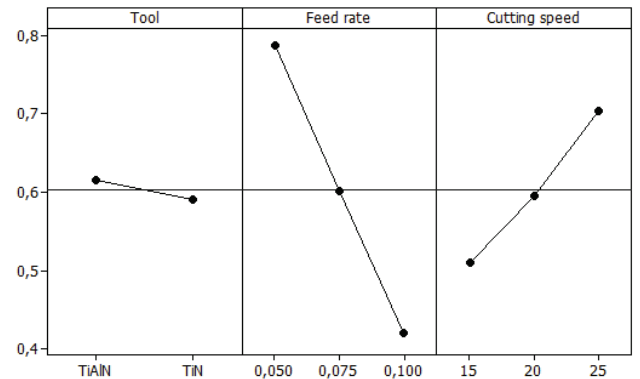


Figure 4 Impact ratings: Cutting tool, feed rate (f) and cutting speed (V_c)

3.3.2 Analysis of variance (ANOVA)

One of the analysis methods used in the investigation of the effect of different parameters on the result is analysis of variance (ANOVA). The percentage contributions of the parameters affecting ANOVA output values are given in Tab. 6.

In Tab. 6 effect degrees of the parameters affecting the cutting force and surface roughness were determined. The effect degrees of each parameter were obtained by using variance analysis (ANOVA). The most effective parameter affecting the cutting force and surface roughness came out to be feed rate with 69.62%.

3.3.3 Confirmation Test

From the studies made (by the aid of Taguchi) according to "the lowest-the best" equation, $A1B1C3$ were found out as the optimum cutting parameters depending on the obtained GRA degrees. Verification tests were carried out with respect to these parameters. Verification tests were made three times and the averages were taken. In the end, the starting and estimated GRA results in Tab. 7 were obtained.

From Tab. 7 it is seen that verification test results found out according to the test results (depending on the starting parameters) were improved by 53% on average.

Table 6 ANOVA for grey relational grade (GRG)

Source	df	SS	MS	F-test	p-coefficient	PCR / %
A	1	0.002783	0.002783	0.68	0.427	0
B	2	0.405883	0.202941	49.36	0	69.62
C	2	0.113188	0.056594	13.76	0.001	18.38
Error	12	0.049342	0.004112			14.46
Total	17	0.571196				100

Table 7 Results of confirmation experiment

Level	Initial cutting parameters	Optimal cutting parameters	
		Prediction	Experimental
	A2B2C2	A1B1C3	A1B1C3
Ra	1.07		1.04
Fc	642.21		497.78
GRG	0.490	0.900860	0.753

The improvement in GRG = 0.263

The percentage improvement in GRG = 53%

4 CONCLUSIONS

The effects of cutting parameters on surface roughness and cutting forces in the drilling of duplex stainless steels were investigated and the results obtained with this study are summarized below:

- According to ANOVA results, the most significant factor in affecting the surface roughness and cutting force was the feed rate having a percentage contribution of 69.62%.
- The confirmation experiments were performed to verify the optimal cutting parameters. The improvement of GRG from the initial cutting parameters to the optimal cutting parameters was percentage improvement in GRG = 53%
- The optimum parameters for the maximum surface roughness and cutting force were computed by using the Grey Relation Analysis (GRA). The optimum parameters for surface roughness and cutting force efficiencies were obtained as A1B1C3.
- The confirmation results have indicated a good agreement between experimental and predicted results within the ranges of the applied parameters.

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