Chapter 9
Influence of Process Parameters on Surface Roughness Hole Diameter Error and Burr Height in Drilling of 304L Stainless Steel

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Abstract Machining of stainless steel materials is known to be very difficult due to the formation of BUE, low heat conductivity, high ductility, high tensile strength, high fracture toughness, high work-hardening rates, and high modulus of elasticity and reactivity at high cutting speed with most tool materials. This work aims to study the influence of process parameters such as spindle speed, feed rate, point angle and cutting tool on surface roughness, hole diameter error, burr height, and chip study during dry drilling of 304L stainless steel. Dry drilling is considered to be environmentally friendly drilling process. The cutting tools considered was M2 HSS drills and these drills were subjected to deep cryogenic treated at −191 °C for 20 h and post-tempered at 180 °C for 2 h. Experiments have been conducted according to full factorial design. From analysis of variance (ANOVA), the most dominant parameters for surface roughness, burr height, and hole diameter error were found to be cutting tools. Furthermore, experiments have been conducted to evaluate tool life of untreated drill, cryogenic treated one-tempered drills, and cryogenic treated two-tempered drills at a constant speed of 650 rpm, feed rate = 15 mm/min, and point angle 118 °C. Compared to untreated drills, the enhancement in tool life was 53.84% for DCT1T drills and 92.30% for DCT2T drills. Compared to DCT1T, enhancement in tool life was 23.8% for DCT2T drills.

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Nomenclature

HSS	High-speed steel
UT	Untreated
DCT1T	Deep cryogenic treatment one tempered
DCT2T	Deep cryogenic treatment two tempered

9.1 Introduction

Drilling is one of the most common and complex machining processes to produce holes in a variety of manufacturing industries including aerospace, aircraft, automotive, machinery manufacturing, and in tool die industries [1, 2]. A study of 145 companies related to the machining sector showed that the drilling process is one of the most important one, due to both number of operations and the machining time consumed. The importance of this process is even higher in heat exchanger, die making, and in aircraft manufacturing industries [3]. Dry drilling is a process in which machining was done without employing cutting fluid [4]. Dry drilling reduces series of harmful environmental effects caused by cutting fluid. Dry machining is the best solution from an environmental point of view [5]. The dry machining has the advantage of non-pollution of the water and air, no problem in disposal of the cutting fluid, and no danger to the health of the operator. However, with dry machining one has to adopt the measures suitable to compensate the primary functions of the cooling lubricant.

9.2 Background and Review

Over the past few decades, the use of austenitic stainless steel is increasing considerably. Due to this, the number of research articles concerning the machinability of this material is increasing considerably [6]. Among the austenitic stainless steels, AISI 304L stainless steel has widely used engineering material application such as food processing equipment, aircraft, aerospace, pharmaceutical companies, and oil and gas industries due to their significant advantages like high corrosion resistance, high toughness, and high pitting corrosion resistance. The enhancement in properties of 304L steel leads to difficulty in machining, due to high work-hardening rate, high ductility, BUE formation, poor surface integrity, high tool wear, and poor surface finish [1, 7]. During dry drilling, tool wear/tool life is a major problem. The enhancement of tool life was achieved through cryogenic treatment of cutting tools [8]. Various authors reported that enhancement in tool life for cryogenic treated drill was 716%. Cryogenic treatment refers to the treatment of materials at very low temperatures, generally at −196 °C for about 24 h and cools slowly to room temperature. Various researches have been conducted during drilling of material; some of the previous studies conducted by previous authors are presented in Table 9.1.

Table 9.1 Summary of previous studies conducted on drilling

Refs.	Material	Drill size/coating	Cutting parameters	Methodology	Objectives
Garg et al. [9]	316L SS	Uncoated HSS	Cutting speed = 8, 12, 16 m/min Feed = 0.04, 0.08, 0.12 mm/rev Drill dia. = 10, 16, 22 mm Point angle = 118°, 126°, 134° Lip clearance angle = 8°, 10°, 12°	MGGP and S-MGGP	BH, BT
Kilickap et al. [10]	Drilling 1045	8 mm TiN coated HSS	Cutting speed = 5, 10, 15 m/min Feed = 0.1, 0.2, 0.3 mm/rev Cutting environment = MQL, Comp. air, dry	RSM and GA	SR
Kaplan et al. [11]	AISI D2 and AISI D3	10 mm uncoated HSS, 118° point angle, 30° helix angle	Speed = 5, 10, 15 m/min Feed 0.04, 0.05, 0.06 mm/rev Number of holes = 20 Drill length = 133, 184 mm Workpiece hardness 20, 28 HRC	Factorial design	AA, TW
Cicek et al. [12]	304 SS	6 mm uncoated M35 HSS, 118° point Angle, 30° Helix angle	Cutting speed = 12, 14, 16 m/min Feed = 0.04, 0.06, 0.08 mm/rev Cutting tools = CHT, CT, CTT	Taguchi and RSM	SR, RE
Prakash et al. [13]	MDF Board	Solid carbide step drill, 140° point angle, 30° Helix angle	Feed = 100, 300, 500 mm/min Speed = 1000, 3000, 5000 rpm Drill dia. = 4, 8, 12 mm	Taguchi and GRA	SR, DL
Gowda et al. [14]	Epoxy-Si_3N_4	Uncoated HSS,	% Vol of Si_3N_4 = 0, 6, 10 Feed = 0.095, 0.19, 0.285 mm/rev Speed = 360, 490, 680 rpm Drill dia. = 6, 8, 10 mm Machining time = 30, 60, 90 s	Taguchi	SR, CR, CY
Aized and Amjad [15]	AISI D2	8 mm uncoated HSS, 118° point angle	Feed = 10, 15, 20 mm/min Speed = 200, 500, 800 rpm Depth of drilling step = 4, 8, 12 mm	RSM	SR, RE, CY, HDE

Fig. 9.1 Experimental setup

CHT Conventional Heat Treated, CT Cryogenic treated, CTT Cryogenic treated tempered, SR Surface roughness, RE Roundness error, AA Acceleration amplitude, TW Tool wear, BH Burr height, BT Burr thickness, CR Circularity, CY Cylindricity, HDE Hole diameter error, DL Delamination. RSM Response surface methodology, GA Genetic Algorithm, MGGP Multi Gene Genetic programming, GRA Grey relational analysis.

From the above literature review, it was concluded that influence of drilling cutting parameters on surface roughness, hole diameter error, and burr height have not been reported on drilling of 304L stainless steel. To fill this literature gap, this study was conducted.

9.3 Experimental Setup

The experiments were conducted on vertical milling center make-Hartford model no PRO-1000A. The spindle drive motor is of 7.5 KW for this machine. The cutting feed rate of this machine ranges from 1 to 12 m/min. Spindle speed is in the range from 40 to 8000 rpm. The experimental setup is shown in Fig. 9.1. The workpiece is 304L stainless steel. The chemical composition of the workpiece is as follows (wt%): C 0.0232, Si 0.439, Mn 1.66, P 0.0343, S 0.00330, Cu 0.2866, Cr 18.02, Mo 0.2007, Ni 8.22, Al 0.008130, Nb 0.0244, Ti < 0.0100, Sn 0.0087, V 0.1154, Co 0.1876, and W < 0.05 Fe balance. M2 HSS drill bits were chosen as a tool material for studying the effect of cryogenic treatment. The chemical composition of drill bits is as follows (wt%): C 0.88, Mn 0.22, Si 0.45, Cr 4.50, Ni 0.20, Mo 5.45, W 6.55, V 2.10, and Cu 0.1 Fe balance. M2 HSS drill bits double helical two flutes are used as specimens. In order to maintain initial condition, each experiment was conducted using a new drill. The geometry of drill bit was as shown in Table 9.2.

Table 9.2 Geometry of M2 HSS drill

Name	Designation
Tool material	M2 HSS
Tool reference	DIN1897
Helix angle	29°
Point angle	118°, 130°, 142°
Diameter	6 mm

9.3.1 Cryogenic Treatment

Cryogenic treatment on M2 HSS drill was done through cryogenic processor model no CP220LH having a cylinder filled with liquid nitrogen made of Taylor-Wharton with model no WH-240 (IAPHT, Ludhiana). This set up can reach up to −191 °C as lowermost temperature for deep cryogenic treatment. Cryogenic processor setup is shown in Fig. 9.2.

The Sequence of the cryogenic treatment for HSS is as following:

Slow cooling of the tools at the rate of 1 °C/min to the temperature (−186 ± 5 °C), i.e., soaking temperature. Hold material at this temperature for 20 h, i.e., soaking time. Warming up of the material to the room temperature at a slow rate of 1 °C/min. Tempering is to be done after cryogenic treatment at the temperature of

Fig. 9.2 Cryogenic processor

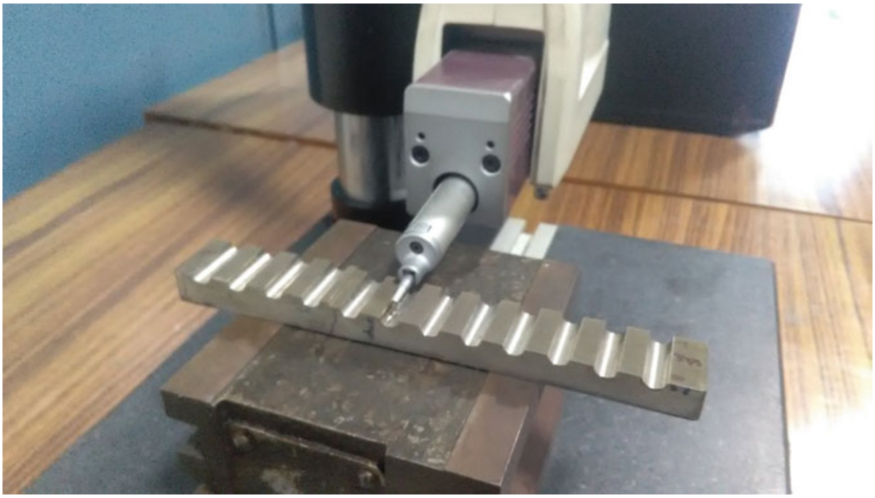


Fig. 9.3 Surface roughness tester

180 °C and a post-tempering period of 1 h. Double tempering is to be done after cryogenic treatment at the temperature of 180 °C and a post-tempering period of 1 h to some cutting tools. Liquid nitrogen gas was used as a cryogenic agent for deep cryogenic treatment.

Surface roughness was measured through Mitutoyo model SJ-400 surface roughness tester and hole diameter was measured by CMM Machine (Make: Wanzel). Burr height was measured through digital caliper. For measuring surface roughness, the plates were cut parallel to hole axis. The sampling length was kept at 4 mm and cut-off length was kept at 0.8 mm. Device for measurement of surface roughness and hole diameter are shown in Fig. 9.3 and Fig. 9.4, respectively.

Factors and their levels used for experimentation are shown in Table 9.3.

9.4 Methodology

On the basis of factor and their levels, the proper design of experiments is to be selected. Here four factors and two levels are considered for this study, along with four center points for checking of curvature. The experiment has been conducted according to full factorial design, i.e., 16 runs for factorial and 4 runs for center points. The total experiments conducted were 20.

Fig. 9.4 Coordinate measuring machine for measurement of hole diameter error

Table 9.3 Factors and their levels of interest

Factors designation	Name	Low	Medium	High
A	Spindle speed (rpm)	450	550	650
B	Feed rate (mm/min)	15	30	45
C	Point angle (degree)	118°	130°	142°
D	Cutting tools	Untreated	Single tempered	Double tempered

9.5 Experimental Results and Analysis

The experimental designs and experimental results for surface roughness, hole diameter error, and burr height are shown in Table 9.4. The experiments were conducted according to full factorial design with the addition of center points for checking curvature. The results were analyzed through Minitab 16 software. The main effects plot and interaction effects plot for surface roughness, hole diameter, and burr height are shown in Fig. 9.5, Fig. 9.6 and Fig. 9.7, respectively.

Table 9.4 Experimental results for surface roughness, hole diameter error and burr height

Sr. no.	Spindle speed (rpm)	Feed rate (mm/rev)	Point angle (degree)	Cutting tool	Surface rough-ness	Hole diameter error (mm)	Burr height (mm)
1	450	15	142	DCT2T	3.27	6.2890	0.048
2	650	45	118	UT	3.78	6.0248	0.060
3	450	45	118	UT	3.98	6.0267	0.080
4	650	15	142	DCT2T	2.98	6.3346	0.011
5	450	15	142	UT	3.58	6.0992	0.140
6	650	15	142	UT	3.67	6.1245	0.135
7	450	15	118	UT	3.53	6.1023	0.020
8	550	30	130	DCT1T	3.42	6.2134	0.058
9	650	45	118	DCT2T	3.23	6.1970	0.034
10	550	30	130	DCT1T	3.48	6.2009	0.062
11	450	15	118	DCT2T	3.12	6.2564	0.041
12	650	45	142	UT	3.71	6.0879	0.148
13	550	30	130	DCT1T	3.46	6.2285	0.063
14	550	30	130	DCT1T	3.41	6.2108	0.061
15	450	45	142	DCT2T	3.31	6.1992	0.054
16	650	15	118	UT	3.49	6.1102	0.067
17	450	45	142	UT	4.13	6.0578	0.089
18	650	15	118	DCT2T	3.02	6.2348	0.049
19	650	45	142	DCT2T	3.11	6.2654	0.059
20	450	45	118	DCT2T	3.33	6.2109	0.039

ANOVA is the most widely used tool that checks the significance of model. When P-value is up to 0.05, the controllable variables and interactions effects are comparable. The results for ANOVA for surface roughness and hole diameter error are shown in Tables 9.5, 9.6 and 9.7. This analysis was carried out at 95% confidence interval and at 5% significance level.

The Model F-value of 20.81 as shown in Table 9.5 implies that model is significant for surface roughness. In addition, spindle speed had a significant effect (P-value < 0.05) on the surface roughness of hole. Higher spindle speeds are preferable for the better surface as shown in main effects plot of surface roughness Fig. 9.5a.

Feed rate had a significant effect (P-value < 0.05) on the surface roughness of hole. From the main effects plot Fig. 9.5a better surface can be obtained at lower feed rate. Surface roughness lowers down on decreasing the feed rate.

Cutting tool had a significant effect on the surface roughness of the hole as the P-value from Table 9.5 is less than 0.05. Main effects plot of surface roughness Fig. 9.5a

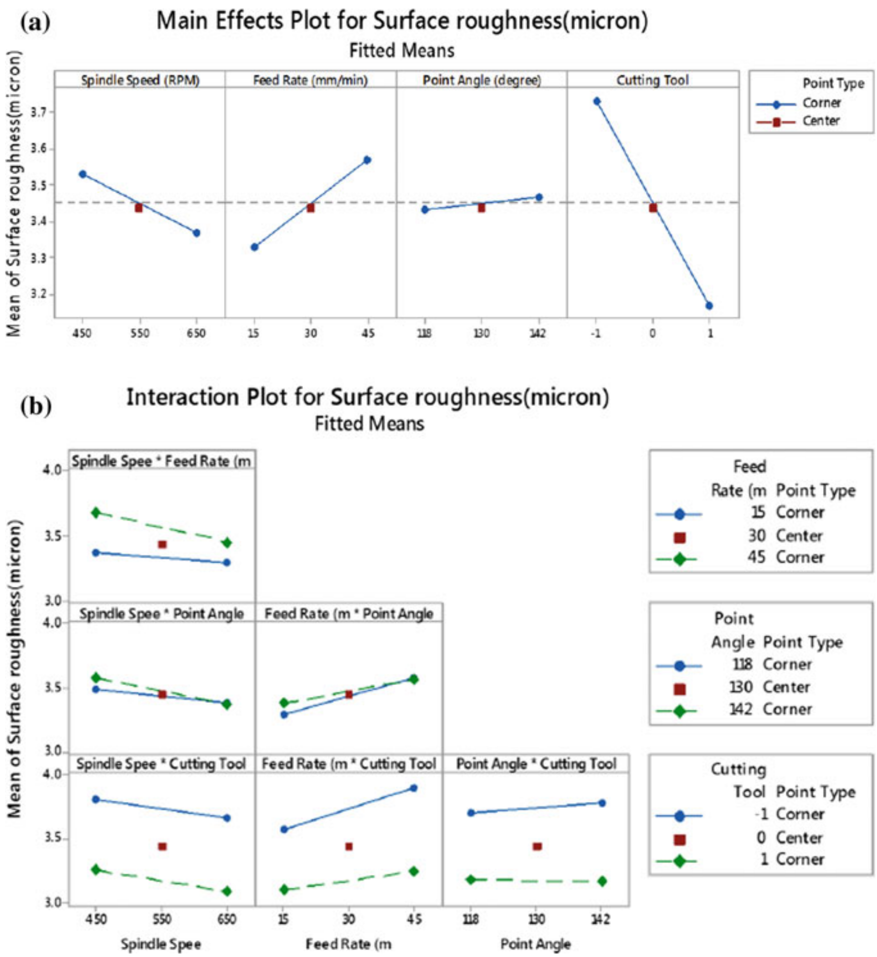


Fig. 9.5 **a** Main effects plot and **b** interaction effects plot for surface roughness

shows that double-tempered cryogenically treated tools give the best surface finish and lowest surface roughness.

No interaction between factors had a significant effect on the surface roughness of hole as shown in interaction plot of surface roughness Fig. 9.5b and also in Table 9.5. The P-value of interactions is more than 0.05. But in the interaction plot, feed rate with point angle showed some interaction at (10% significance level) but not significant for surface roughness of hole. Similar results were observed by Vipin et al. [16, 17].

The Model F-value of 39.72 as shown in Table 9.6 implies that model is significant for hole diameter error. Spindle speed had no significant effect (P-value > 0.05) on hole diameter but low cutting speed can give better results for hole diameter for close tolerances.

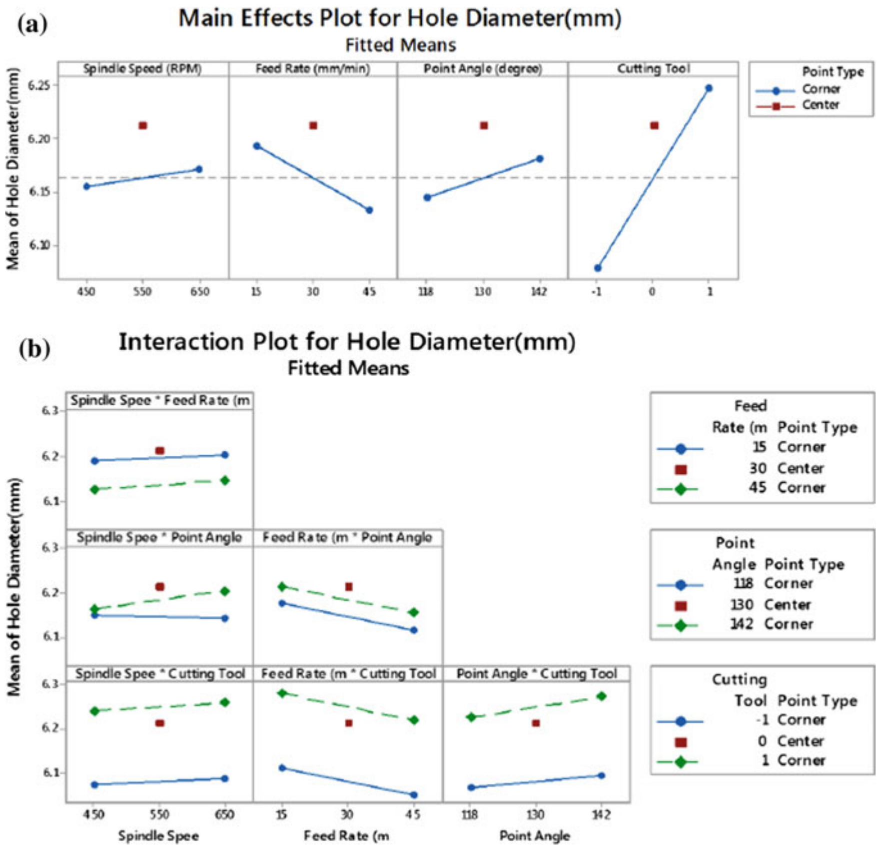


Fig. 9.6 **a** Main effects plot and **b** interaction effects plot for hole diameter error

Spindle speed in interaction with a point angle of drill had a significant effect on the hole diameter as shown in the chart of interaction plot of hole diameter Fig. 9.6a and in Table 9.6.

Feed rate had significant effect (P-value < 0.05) on hole diameter. From the chart of main effects plot, better hole diameter can be obtained at higher feed rate. Hole diameter gives better results on increasing the feed rate. Point angle of the drill had also significant effect (P-value < 0.05) on the diameter of the hole. The better diameter of closer tolerances can be obtained at lower point angle. On increasing the point angle, the diameter of the hole is also increasing.

Cutting tool also had a significant effect (P-value < 0.05) on the diameter of the hole. The better diameter of closer tolerances was obtained by the untreated tool. After the cryogenic treatment, there was an expansion in the volume of M2 HSS, which increases the diameter of the cutting tool. Similar results were observed by Vipin et al. [16, 17].

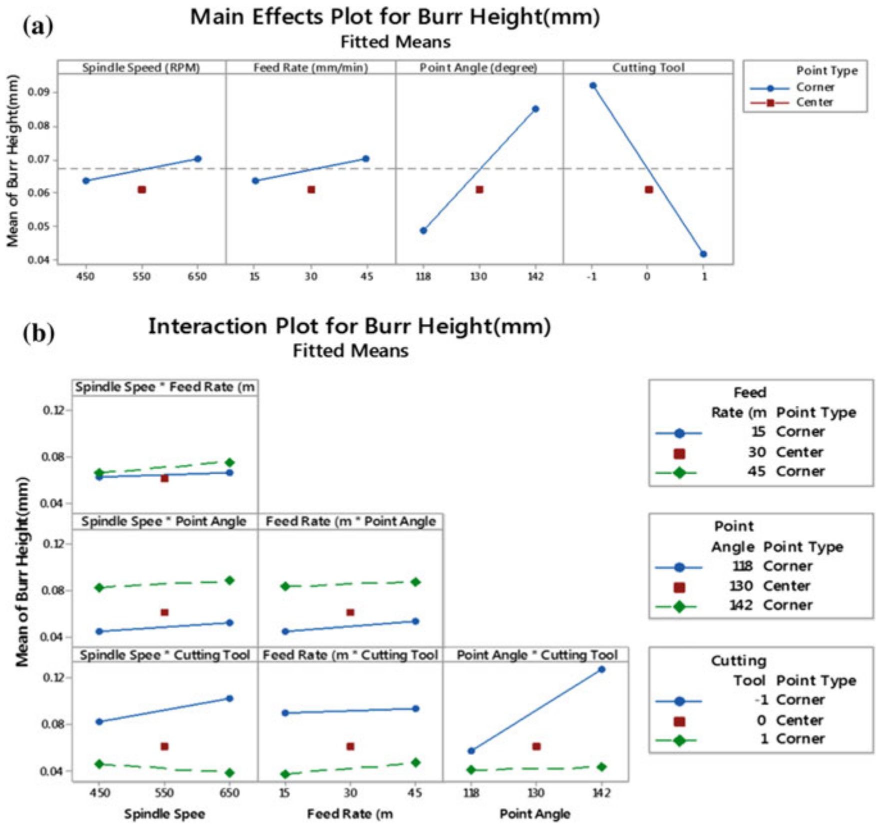


Fig. 9.7 **a** Main effects plot and **b** interaction effects plot for burr height

The Model F-value of 3.52 as shown in Table 9.7 implies that model is significant for burr height. Spindle speed had no significant effect (P-value > 0.05) on burr height but low cutting speed can give better results for burr height. Point angle had significant effect (P-value < 0.05) on burr height. The main effects plot also confirmed that low burr height can be obtained at lower point angle. Burr height decreases on decreasing the point angle. Cutting tools had significant effect on the burr height. The main effects plot also confirmed that low burr height was obtained on drilling cryogenically treated double-tempered drills.

From interaction plot, it can be seen that point angle in interaction with a cutting tool had a significant effect on burr height. Spindle speed in interaction with cutting tools had some effect on burr height as shown in the chart of interaction plot of burr height Fig. 9.7c and in Table 9.7.

Table 9.5 Analysis of variance for surface roughness

Source	DF	SS	MS	F-value	P-value
Model	11	1.68287	0.15299	20.81	0.000
A	1	0.09923	0.09923	13.49	0.006
B	1	0.23040	0.23040	31.33	0.001
C	1	0.00490	0.00490	0.67	0.438
D	1	1.26562	1.26562	172.12	0.000
AB	1	0.02103	0.02103	2.86	0.129
AC	1	0.00903	0.00903	1.23	0.300
AD	1	0.00090	0.00090	0.12	0.735
BC	1	0.01000	0.01000	1.36	0.277
BD	1	0.03422	0.03422	4.65	0.063
CD	1	0.00722	0.00722	0.98	0.351
Curvature	1	0.00032	0.00032	0.04	0.840
Error	8	0.05882	0.00735		
Total	19	1.74170			

R-sq = 96.62%, R-sq (adj) = 91.98%, R-sq (Pred) = 67.01%, S = 0.0857504

Table 9.6 Analysis of variance for hole diameter error

Source	DF	SS	MS	F-value	P-value
Model	11	0.146432	0.013312	39.72	0.000
A	1	0.001185	0.001185	3.54	0.097
B	1	0.014478	0.014478	43.20	0.000
C	1	0.005421	0.005421	16.18	0.004
D	1	0.114565	0.114565	341.87	0.000
AB	1	0.000034	0.000034	0.10	0.758
AC	1	0.002418	0.002418	7.22	0.028
AD	1	0.000014	0.000014	0.04	0.844
BC	1	0.000003	0.000003	0.01	0.923
BD	1	0.000001	0.000001	0.00	0.965
CD	1	0.000438	0.000438	1.31	0.286
Curvature	1	0.007874	0.007874	23.50	0.001
Error	8	0.002681	0.000335		
Total	19	0.149112			

R-sq = 98.20%, R-sq (adj) = 95.73%, R-sq (Pred) = 83.81%, S = 0.0183061

Table 9.7 Analysis of variance for burr height

Source	DF	SS	MS	F-value	P-value
Model	11	0.021680	0.001971	3.52	0.042
A	1	0.000169	0.000169	0.30	0.598
B	1	0.000169	0.000169	0.30	0.598
C	1	0.005402	0.005402	9.64	0.015
D	1	0.010201	0.010201	18.21	0.003
AB	1	0.000042	0.000042	0.08	0.791
AC	1	0.000004	0.000004	0.01	0.935
AD	1	0.000756	0.000756	1.35	0.279
BC	1	0.000025	0.000025	0.04	0.838
BD	1	0.000030	0.000030	0.05	0.822
CD	1	0.004761	0.004761	8.50	0.019
Curvature	1	0.000120	0.000120	0.21	0.656
Error	8	0.004482	0.000335		
Total	19	0.026162			

R-sq = 82.87%

Table 9.8 No of holes drilled by different cutting tools along their tool life increment

Sample no.	Specimen	No of holes drilled	% increment in tool life over untreated	% increment in tool life over single tempered
1	Untreated	13	0	–
2	Single tempered	20	53.84	0
3	Double tempered	25	92.30	23.8

9.6 Tool Life

Based on the above study the process parameters considered to evaluate tool life were Spindle speed was taken 650 rpm, the feed rate was 15 mm/min, and point angle of drills was 118°. Each cutting tool from a different category (untreated, single tempered, and double tempered) was used to make holes in this condition. The obtained results are shown in Table 9.8 and Fig. 9.8.

The enhancement of tool life was obtained to be 53.84 and 92.30% over the untreated tool for DCT1T and DCT2T.

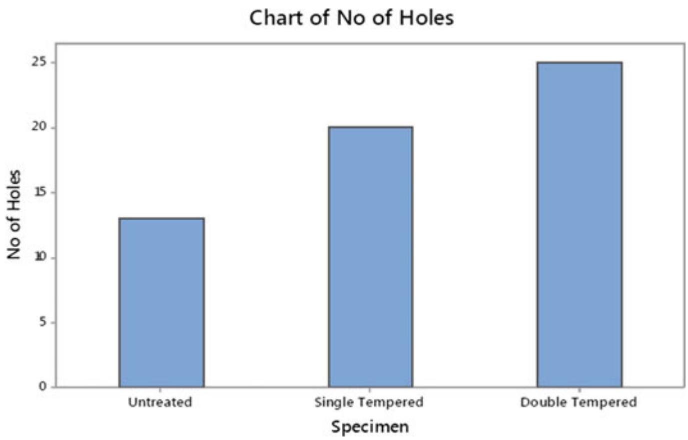
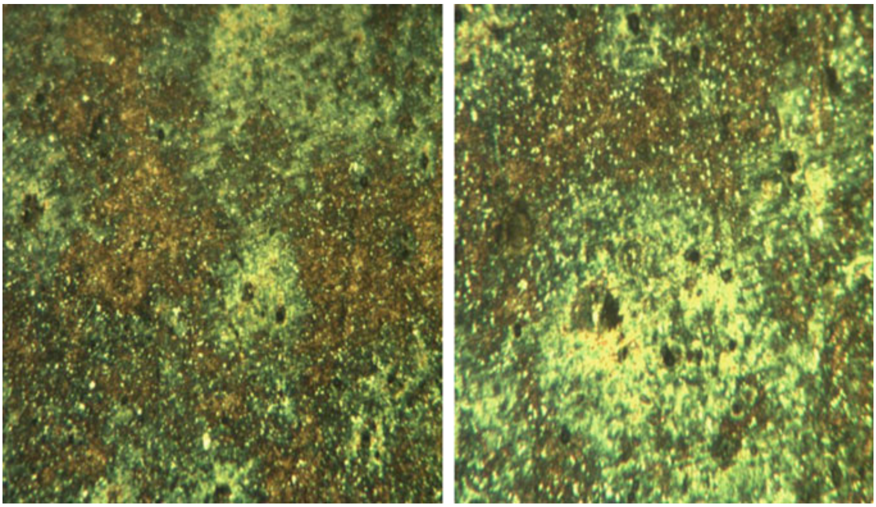


Fig. 9.8 Bar graph representing no. of holes corresponding cutting tool

9.7 Microstructure

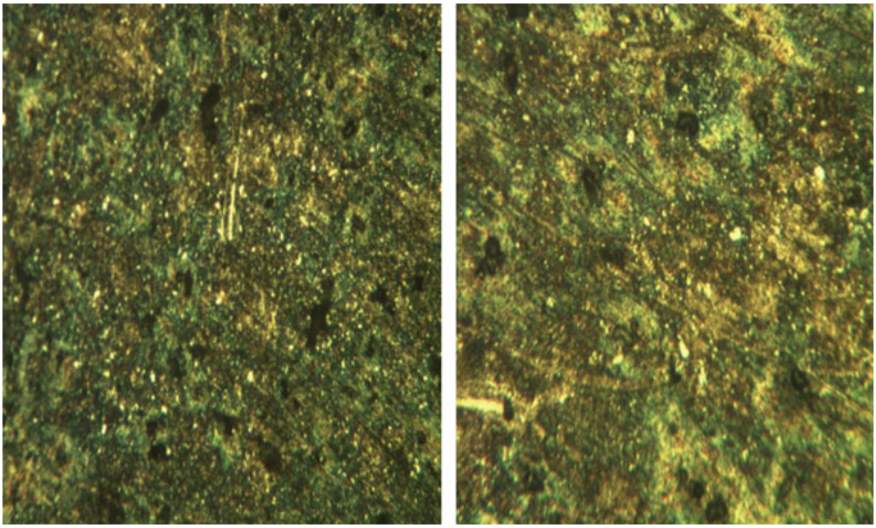
Microstructure images of untreated, single-tempered, and double-tempered tools were taken with the help of optical microscope as shown in Figs. 9.9, 9.10, and 9.11, respectively.

Figures 9.9, 9.10, and 9.11 show the microstructures of M2 grade HSS samples such as untreated drills, single-tempered drill, and two-tempered drill. From Fig. 9.9



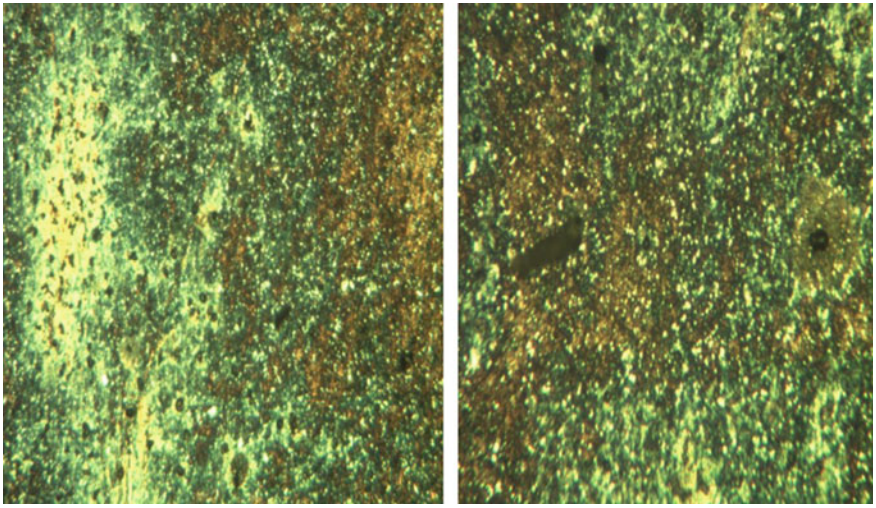
(a) Untreated drill at 100x (b) untreated drill at 200x

Fig. 9.9 Microstructure of untreated drill



(a) single tempered drill at 100x (b) single tempered at 200x

Fig. 9.10 Microstructure of single-tempered drill



(a) Double tempered drill at 100x (b) Double tempered drill at 200x

Fig. 9.11 Microstructure of double-tempered drill

Fig. 9.12 Long ribbon chips

it can be observed that presence of retained austenite, primary carbide and secondary carbide. The micro-hardness of untreated sample was observed to be 1010.067HV1. The hardness of single treated drill was observed to be 1094.4 which was due to the transformation of retained austenite into martensite and precipitation of fine carbide. But decrease in hardness of two-tempered drills was observed to be 1083.73. This was due to the formation of softer carbide.

9.8 Chip Study

Following types of chips are produced while machining of stainless steel 304L are shown in Figs. 9.12, 9.13, and 9.14, respectively.

During drilling of stainless steel, continuous chips are produced. Continuous chips are of two types: (1) continuous chip with tight helix angle and (2) continuous chip with loose helix angle.

9.9 Conclusions

This study investigates the influence of process parameters such as spindle speed, feed rate, point angle, and a cutting tool on surface roughness, hole diameter error, and burr height during dry drilling of 304L stainless steel. The following conclusions have been drawn from the experimental work:

Fig. 9.13 Ribbon chips

Fig. 9.14 Broken down chips

- From the experimental trials, it was concluded that the most influencing parameter for surface roughness, hole diameter error, and burr height was cutting tool with a percentage contribution of 72.66%, 76.83%, and 40%, respectively, followed by feed rate with a percentage contribution of 13.22% and 9.70%, respectively, for surface roughness and hole diameter error, and point angle (20.64%) for burr height.
- The optimal parameter condition for surface roughness was obtained at 650 rpm speed, 15 mm/min feed rate, 118° point angle, and DCT2T drill as a cutting tool.
- The optimal parameter condition for hole diameter error was obtained at 650 rpm speed, 45 mm/min feed rate, 118° point angle, and DCT2T drill as a cutting tool.
- The optimal parameter condition for burr height was obtained at 650 rpm speed, 15 mm/min feed rate, 118° point angle, and DCT2T drill as a cutting tool.
- Chips obtained were long ribbon chips, ribbon type chips, and broken down chips.
- The enhancement of tool life was 53.84% and 92.30%, respectively, for DCT1T and DCT2T drills compared to untreated drills.
- The experimental results showed that full factorial design has successfully been used for modeling and optimizing the cutting parameters in the dry drilling of 304L stainless steels within the 95% confidence interval.

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