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Performances of cryo-treated and untreated cutting tools in machining of AA7075 aerospace aluminium alloy

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Abstract: The quality of drilled holes in aluminium alloys used in the aerospace industry is vital to ensure high-precision structural integrity. For this reason, optimum selection of cost-effective cutting tools and cutting parameters is of great importance. Nowadays, due to their high cost and supply difficulties, there is a great interest in improving the performance of traditional HSS cutting tools as an alternative to ceramic, carbide and coated cutting tools. HSS cutting tools are widely used in different industries due to their cost-effectiveness and suitability to improve tool performance. In this research, the performances of cryo-treated (DC&T) and untreated (UT) HSS cutting tools used in dry machining of AA7075 aluminium alloys were investigated. Thanks to DC&T processes applied to HSS cutting tool, improvements have occurred in its microstructure. The hardness value of HSS cutting tool increased by 6.89% with the effect of DC&T processes applied. When the highest and lowest Ra values obtained using DC&T and UT HSS cutting tools were compared, it was seen that DC&T HSS cutting tool performed better by 11.05% and 25.91%, respectively. It has been determined that the hole surface quality of the aluminium workpiece machined with DC&T and UT HSS drills is negatively affected by the increase in spindle speed and feed rate. The highest S/N ratios calculated according to Ra values of holes drilled on aluminium workpieces using DC&T and UT HSS cutting tools were found to be -7.12 dB (2.27 µm) and -9.62 dB (3.03 µm), respectively. In the ANOVA analysis, it was determined that the most effective parameters on Ra values were spindle speed (70.62%), tools (18.19%) and feed rate (9.98%), respectively. In the regression analysis, R^2 value for Ra values was calculated as 98.30%. High R^2 value result shows that the model developed is quite successful in estimating Ra values.

Keywords: AA7075, Aerospace alloys, Aluminium, Cryogenic treatment, HSS cutting tools, Machining, Surface roughness

1. Introduction

Aluminium alloys are important consumable materials due to their intense use in industries such as aerospace, automotive, electrics and electronics and marine [1]. These materials have many advantages such as high strength to weight ratio, high corrosion and fatigue resistance, as well as ease of manufacture. Thus, machinability studies on aluminium materials are gaining more and more importance day by day. [2].

Aluminium alloys consist of eight series such as 1000, 2000, 3000, 4000, 5000, 6000, 7000 and 8000 [3]. One of these series, 7000 series aluminium alloys, has the highest strength among all aluminium series. Aluminium alloys (especially 7000 series) in this series are often used in aerospace structures and mobile applications. 7000 series aluminium alloys are based on the Al-Zn-Mg(-Cu) system. Among these Aluminium alloy series, which are used extensively in the aerospace industry, the most well-known is 7075 aluminium alloy [3, 4].

In the aerospace industry, drilling operations (due to the need for millions of holes for riveted and bolted joints) are considered to be the most challenging of all the other machining processes [1, 3]. Because the quality of the drilled holes in these aluminium alloys used for the aerospace industry is vital to ensure high-precision structural integrity [5]. For this reason, optimum selection of tool material and coatings, tool geometry [6], drilling parameters (feed rate and spindle speed) and cutting conditions (wet or dry) [7], and drilling machines are required for high quality machining of aluminium alloys [8].

Nowadays, High Speed Steel (HSS) tools are widely used in different industries due to their cost-effectiveness and suitability to improve tool performance. For this reason, intensive researches are carried out on HSS cutting tools [9, 10].

Chemical compositions and microstructures determine the properties of HSS steels and other materials. Hence,

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their chemical composition or microstructure is changed to improve the properties of HSS steels [9, 11]. The general trend is in favour of microstructural changes as it is easier than changing their chemical composition. For this purpose, tool steels (HSS steels) are traditionally heat-treated to improve their microstructure [11, 12]. However, in conventionally produced tool steels (HSS tools), a low percentage of austenite (soft phase) remains. This soft phase, also known as retained austenite, has negative effects on tool life [11, 13]. It is precisely at this stage that a modern process such as cryogenic treatment (CT) is applied to the tool steels to convert the retained austenite to martensite, resulting in significant increases in the performance of the tool steels. CT processes are generally applied to tool steels in two different ways: Shallow (-50°C to -100°C) and deep (-125°C to -196°C). Owing to the shallow and deep cryogenic processes (SC and DC) applied, improvements such as a reduction in the percentage of retained austenite and carbide volume and a more homogeneous distribution of carbides in the microstructure are provided [9-17]. As a result of all these important improvements in the microstructure, there is an increase in the important properties of tool steels such as wear resistance, hardness and tool life [15, 18-20]. Considering tool life, which is one of these very important improvements, it has been stated that even better results (by nearly 110%) have been obtained from TiN coated tools [21].

In this experimental and statistical research, the performances of cryo-treated and untreated HSS drill bits used in drilling AA7075 aluminium alloys were investigated. Within the scope of the study, the processing parameters determined according to Taguchi's L18 (1^2 x 3^2) mixed orthogonal experimental design were employed in order to analyse the obtained results with high accuracy, and also ANOVA and regression analyses were performed.

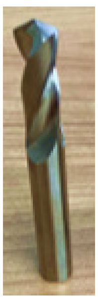
2. Material and Method

Within the scope of this study, AA7075 aluminium alloy plates, which were selected due to their intense use in the aerospace industry [3] and were used as workpieces in this study, were prepared in 65X35X10 (length, width and thickness) mm dimensions. The chemical compositions of AA7075 aluminium alloys used as workpieces in the experimental study are presented in Figure 1. As seen in Figure 1, it is understood that Cu, Mg and Zn elements have a higher percentage by weight than other elements (except the main element Al).

The thermal properties of AA7075 aluminium alloy used are presented in Figure 2. These thermal properties presented were used as helpful information in the evaluation of the surface roughness of the holes drilled on the aluminium workpieces.

In this experimental research, M35 HSS drill bits were used as cutting tools to drill AA7075 aluminium workpieces. These cutting tools were specially chosen for the reasons mentioned above, but also because of their easy

Table 1. Geometric dimensions of HSS drill bits

The dimensions of DC&T and UT cutting tools			
DC&T HSS drill bit	UT HSS drill bit	Diameters (mm)	Ø8
		Point angles (°)	118
		Helix angles (°)	30
		Clearance angles (°)	8

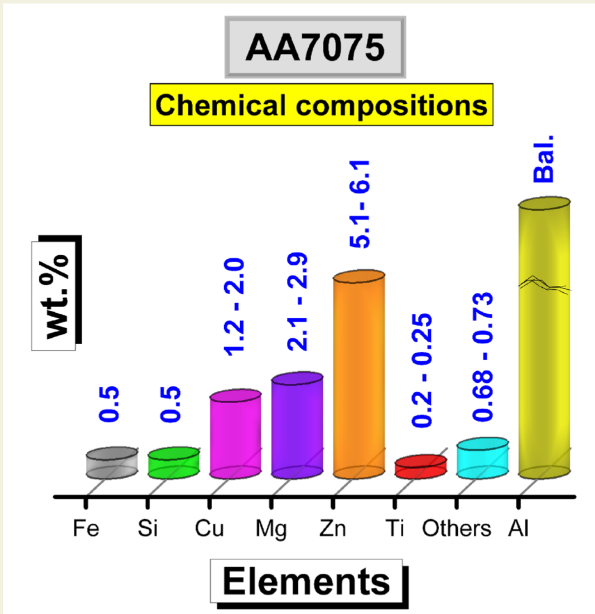


Figure 1. Chemical compositions

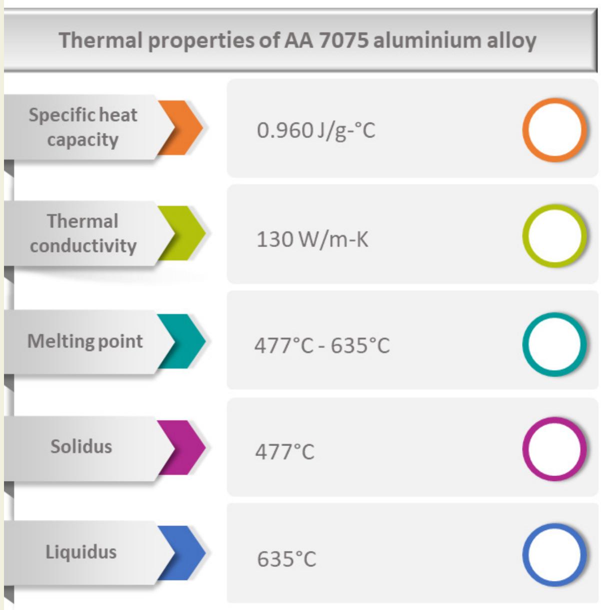


Figure 2. Thermal properties of AA7075

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availability and cost-effectiveness. The geometric dimensions of cryo-treated and untreated (UT) HSS drill bits are given in Table 1. The diameter of HSS drill bits used in this study was especially chosen as 8 mm, since holes are usually drilled in the interval of 5-10 mm in aerospace materials [1].

2.1. Cryogenic Treatment

In this study, the cryogenic treatment and tempering processes (DC&T) applied to HSS cutting tool were determined based on the studies in the literature. The reason for this is that DC&T processes have significant effects on the performance of the cutting tool and an incorrect application has negative effects. The most important reference here is the type (material) of the cutting tool for which DC&T processes are applied [22]. When the studies in the literature are examined, it is seen that the most important parameters for DC&T processes are cooling/heating rate, soaking time, soaking temperature and tempering time, respectively. In studies on HSS steel materials, it has been stated that the most optimum DC&T processes (the cooling/heating rate, soaking time, soaking temperature and tempering time) are 0.5°C/min [23], 24 hours [24], -196°C [25] and 2 hours (at 200°C) [26], respectively. The stages of the deep cryogenic treatment (DC) and tempering (&T) processes applied to HSS cutting tool within the scope of the study are depicted in Figure 3.

2.2. Taguchi Experiment Design

In the manufacturing industries, many new optimization methods have been used in parallel with the developing technology. Among these methods, Taguchi method is one of the most prominent and highly valid. This experimental optimization method, developed by Genichi Taguchi, is a very powerful statistical method. In this experimental design method, it is possible to optimize multiple parameters as the most robust and powerful. With this method, the optimal levels of control factors are determined, their effects on the response are analysed and the relationship between controllable and uncontrollable parameters is revealed [27-32]. In this statistical method, the input factors investigated are taken into account and the effects of these factors on the response functions are revealed through Signal to noise (S/N) ratios. One of the biggest advantages of this method is that the optimum results can be obtained despite the minimum number of experiments. In this method, the unique design of an orthogonal series is used to explain the influences of input factors on objective characteristics based on the minimum cost [33, 34]. Within the scope of this study, an orthogonal array was designed first in order to minimize the number of experiments. Here, 2^1 is chosen because there are two different cutting tools (DC&T and UT HSS cutting tools), and 3^2 is chosen because there are three different spindle speeds (750, 1000, 1250 rev/min) and feed rates (50, 100, 150 mm/min). Therefore, L18 (21 x 32) mixed orthogonal array (OA) is used. The main purpose of this statistical method, which uses L18 orthogonal array, is to obtain the lowest surface roughness. S/N ratio obtained as a result of the statistical analysis indicates the amount of closeness to the target value. Also, the signal indicates the average output, while the noise indicates the deviation of the average output [27].

In this experimental and statistical research, since the surface roughness was aimed at the lowest value, the "The smaller the better" function was preferred. The drilling parameters and levels according to Taguchi design (L18 OA), as well as the "The smaller the better" function (equation 1) is given in Figure 4.

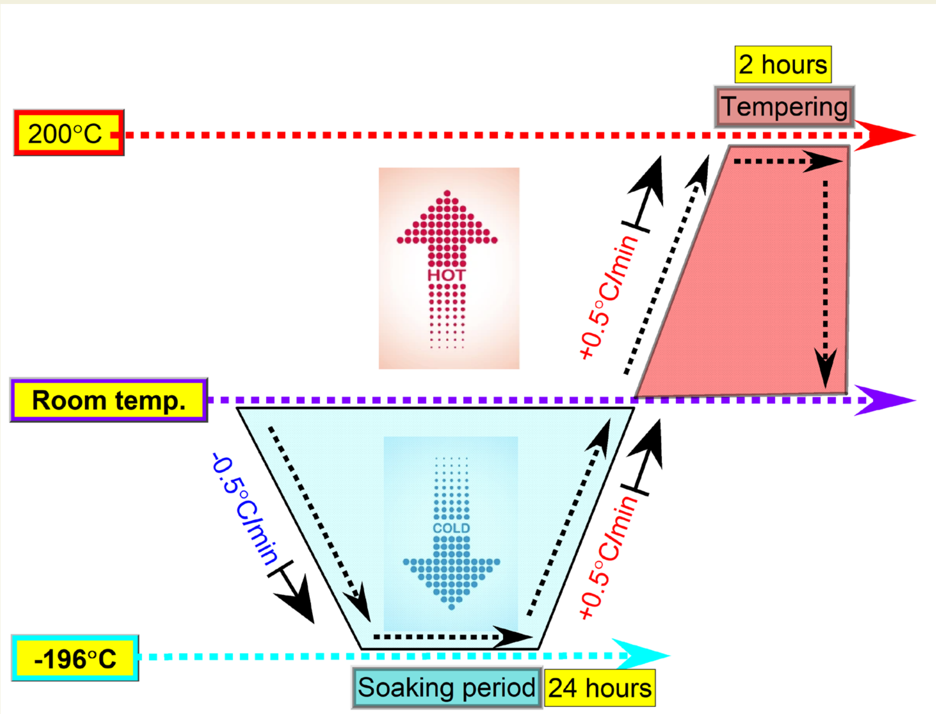

Figure 3. The stages of DC and T processes

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2.3. Drilling Experiments

In this experimental study, drilling tests were carried out on AA7075 aluminium alloys using Maxmill QMC-1050 model computer numerical controlled (CNC) vertical machining center. In recent years, manufacturing industries operating in different fields have attached importance to the machining of workpieces in dry conditions to show that they pay importance to a greener environment [35]. For this purpose, in this study, all drilling operations were performed especially under dry conditions. Moreover, thanks to drilling in dry conditions, both the costs of cooling liquids are avoided and the costs of the manufactured product are reduced [1]. The technical drawing of AA7075 aluminium workpieces machined with DC&T and UT HSS drills, as well as the machining directions are shown in Figure 5. In all experiments conducted within the scope of this study, the ambient temperature was measured as 22°C and the relative humidity was 50%.

2.4. Surface Roughness Measurements

The average surface roughness (Ra) values of the holes drilled in the workpieces are of great importance because they show the dimensional accuracy of the product and the quality of the product. Within the scope of the study, the average values of Ra were taken into consideration, adhering to the general sample acceptance condition [36]. For this purpose, Ra values of the holes drilled on AA7075 aluminium workpieces were measured very precisely using the Hommel Tester T500 brand device. In the measurements of Ra values, the results were calculated by taking the arithmetic average of the measurements made with the device from three different points of each drilled hole.

3. Results and Discussion

3.1. Workpiece and Cutting Tool Hardness Measurements

From the review of the studies in the literature, it is seen that there are changes in the hardness values of the materials that DC&T processes are applied [9, 14]. For this reason, the hardness values of DC&T and UT HSS cutting tools and also workpiece used in the experimental study were measured using Matsuzawa HWMMT-X3 brand microhardness device. After hardness tests were performed at three different locations of each DC&T and UT HSS drills and AA7075 workpiece samples, the arithmetic averages of the obtained results were calculated. As a result of the measurement tests, the calculated hardness values of the cutting tools and the workpiece are depicted in Figure 6. In addition, due to the low hardness value (according to cutting tools) of the aluminium workpiece, it is specified as Brinell hardness value.

As seen in Figure 6, the hardness values of UT HSS drill, DC&T HSS drill and AA7075 aluminium workpiece were measured as 58 HRC, 62 HRC and 60 HB, respectively.

When the effect of DC&T processes applied to HSS drill is examined, it is seen that DC&T processes increase the hardness value of HSS drill by 6.89% (from 58 HRC to 62 HRC). This is explained by the decrease in the percentage

Drilling parameters and levels per Taguchi design (L18 orthogonal array)			
Runs	Tools (Coded value)	Spindle Speed (Coded value)	Feed rate (Coded value)
1	1	1	1
2	1	1	2
3	1	1	3
4	1	2	1
5	1	2	2
6	1	2	3
7	1	3	1
8	1	3	2
9	1	3	3
10	2	1	1
11	2	1	2
12	2	1	3
13	2	2	1
14	2	2	2
15	2	2	3
16	2	3	1
17	2	3	2
18	2	3	3

Drilling parameters and levels				
Parameters	Units	Level 1	Level 2	Level 3
Tools	-	DC&T	UT	-
Spindle Speed	rev/min	750	1000	1250
Feed rate	mm/min	50	100	150

The smaller is better: $$S/N = -10 \log \left(\frac{1}{n} \sum_{i=1}^{n} y_i^2 \right) \quad (1)$$

With,

n: Number of observations,

yi: *i*-the number of observations and

S/N: Signal to noise ratio.

Figure 4. Drilling parameters and levels (L18, OA), and equation 1

of retained austenite and carbide volume by the effect of DC&T processes applied to HSS steels, and a more homogeneous distribution of carbides in the microstructure. As a result of all these important improvements in the microstructure, there is an increase in the important properties of tool steels such as wear resistance, hardness and tool life [9-13, 15]. Considering tool life, which is one of these very important improvements, it is stated that even better results (by nearly 110%) are obtained from TiN coated tools [21].

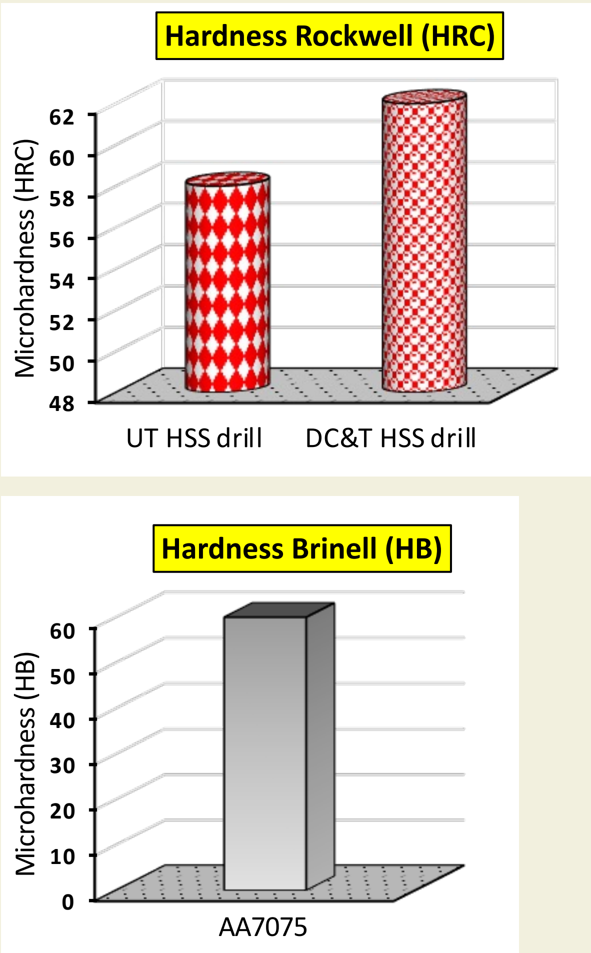


Figure 6. Hardness values of the cutting tools and the workpiece

3.2. Surface Roughness

The quality of the holes drilled into the workpieces is expressed by characteristics such as burr formation, circularity or roundness error, hole size and surface roughness. For this reason, each of these characteristics is specifically investigated [8, 37, 38]. Figure 7 shows the picture prepared to better understand the characteristics of hole quality.

A significant portion (60%) of the components produced for use in aviation is rejected due to unsuitable hole quality. Due to this undesirable situation, intensive researches are carried out to increase the hole quality [1, 37].

In the manufacturing industries, one of the ways to determine the surface quality of drilled workpieces is to measure Ra values of the holes [39]. Holes with the lowest value as a result of the measured Ra values are considered high because they increase the performance and service life of the workpiece [36, 39].

Within the scope of this study, the measured Ra values of the holes drilled on aluminium workpieces with different cutting tools (DC&T and UT HSS drills) and different parameters (spindle speed and feed rate) are depicted in Figure 8.

As depicted in Figure 8, the lowest Ra value obtained with the UT HSS drill used for drilling aluminium workpieces was 3.03 µm. This lowest Ra value was obtained at 750 rev/mm spindle speed and 50 mm/min feed rate parameters, respectively. The highest Ra value obtained by using UT HSS drill is 5.34 µm at 1250 rev/min spindle speed and 150 mm/min feed rate parameters. As a result of drilling tests (determined according to Taguchi experimental design) with UT HSS drill, it was seen that the highest Ra value was 76.23% higher than the lowest Ra value.

On the other hand, the lowest Ra value obtained with DC&T HSS drill used for drilling aluminium workpieces was 2.27 µm. This lowest Ra value was obtained at 750 rev/mm spindle speed and 50 mm/min feed rate parameters, respectively. The highest Ra value obtained by us-

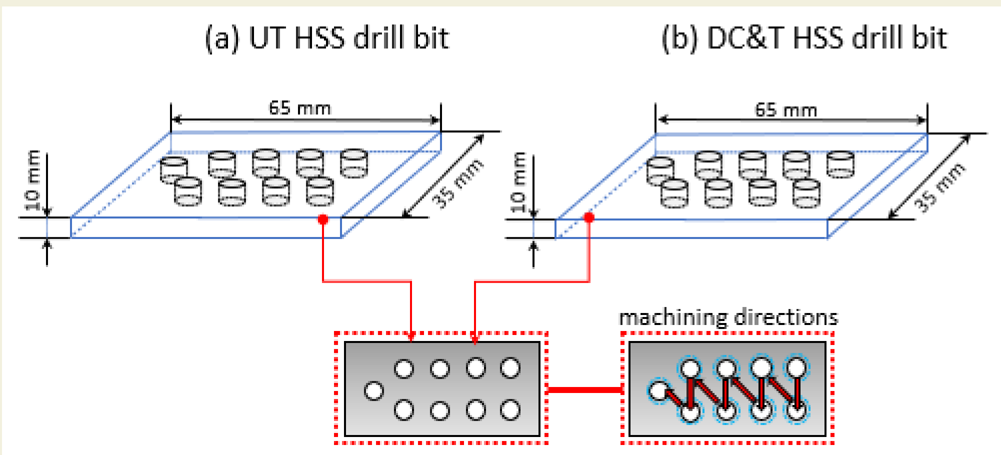


Figure 5. Technical drawing of machined workpieces and machining directions

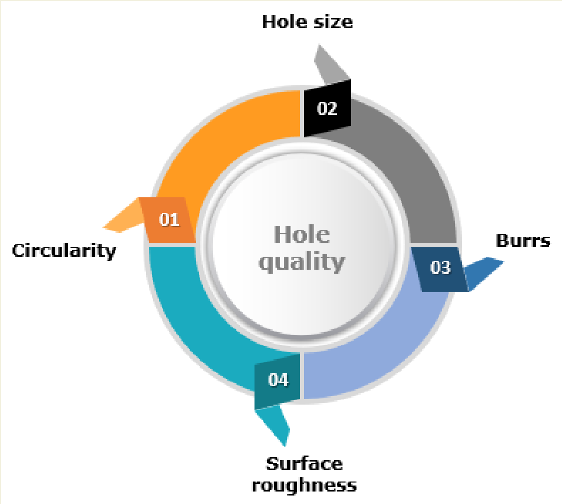


Figure 7. Characteristics of hole quality

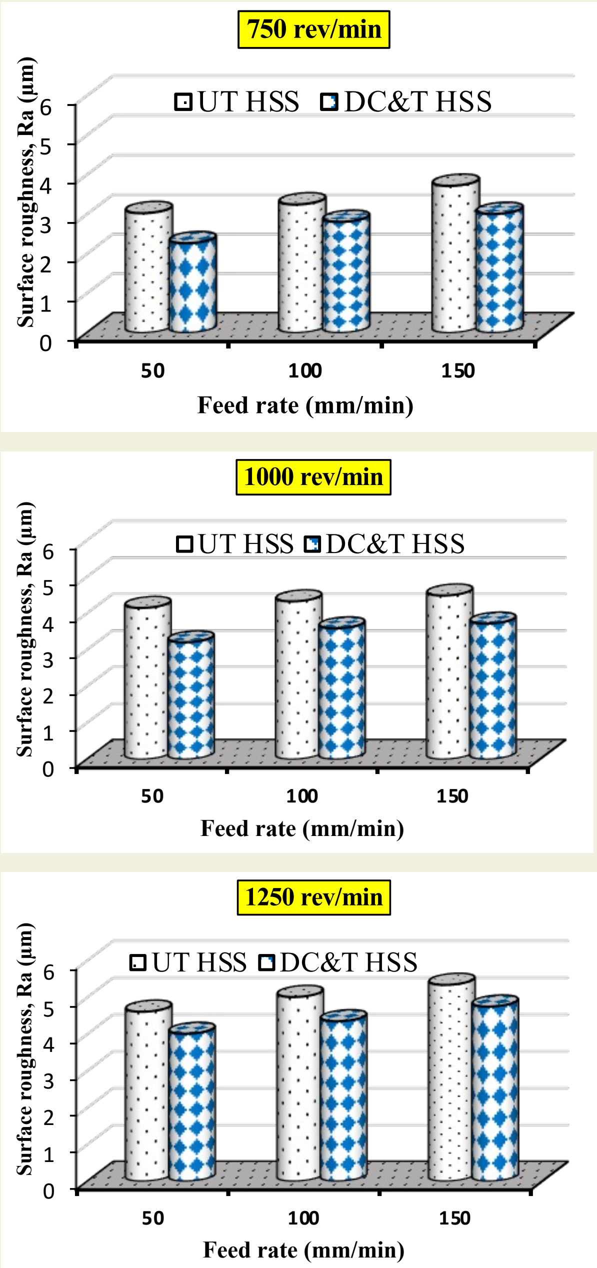


Figure 8. Ra values of aluminium workpieces drilled in different parameters

ing DC&T HSS drill is 4.75 μm at 1250 rev/min spindle speed and 150 mm/min feed rate parameters. As a result of drilling tests with DC&T HSS drill, it was seen that the highest Ra value was 109.25% higher than the lowest Ra value.

As a result, when the highest and lowest Ra values obtained using DC&T and UT HSS drills were compared, it was seen that better performance was obtained with DC&T HSS drill. Moreover, when these results are examined in terms of the highest and lowest Ra values, it is seen that DC&T HSS drill performs 11.05% and 25.91% better, respectively. The reason for this better performance obtained with DC&T HSS drill is DC&T processes applied to HSS drill. As a matter of fact, it is stated in detail in the above section that thanks to DC&T processes applied to HSS drill, significant improvements are achieved in wear resistance, hardness value and cutting tool life. When the results obtained from this study were compared with the studies in the literature (with regard to surface roughness), it was seen that cutting tools with higher hardness and wear resistance performed better [1, 39-41].

During the machining of aluminium alloys, the high feed rate (chip removal speed) negatively affects the surface integrity. The surface roughness that occurs during the machining of aluminium workpieces is directly related to the hardness value (that is, its microstructural features) of the alloy [41-43]. As a matter of fact, it is seen that the hardness value of the aluminium workpiece used in this study is quite low (60 HB). Because the higher the hardness of the aluminium alloy, the less likely the chips will adhere to the cutting surface of the cutting tool. As the most important result of this situation, the surface roughness of the machined aluminium workpiece becomes very low [41, 43, 44]. Due to the high thermal conductivity (Figure 2) and ductility of the aluminium workpiece used in this study, a high rate of BUE (Built-up-edge) occurs in the cutting tools [41, 45]. As a result of this undesirable situation, high roughness values and large burrs occur in the machined aluminium workpieces [41, 43].

On the other hand, during the machining of the aluminium workpiece with the cutting tool, very high temperature values are reached in the cutting zone in a very short time due to the high spindle speed and also the high thermal conductivity of the aluminium workpiece. Due to this undesirable situation, the aluminium workpiece begins to soften and its integrity begins to deteriorate. As a natural consequence of this situation, the surface roughness is negatively affected [41]. In Figure 9, the effects of different drilling parameters and levels on Ra values are depicted comparatively.

As seen in Figure 9, the Ra values of the holes drilled in the aluminium workpiece are negatively affected (increase) as the spindle speed and feed rate increase. This increase in Ra value reaches the highest level (in the red colour zone) especially at 1250 rev/min spindle speed and 150 mm/min feed rate. Moreover, these situations are

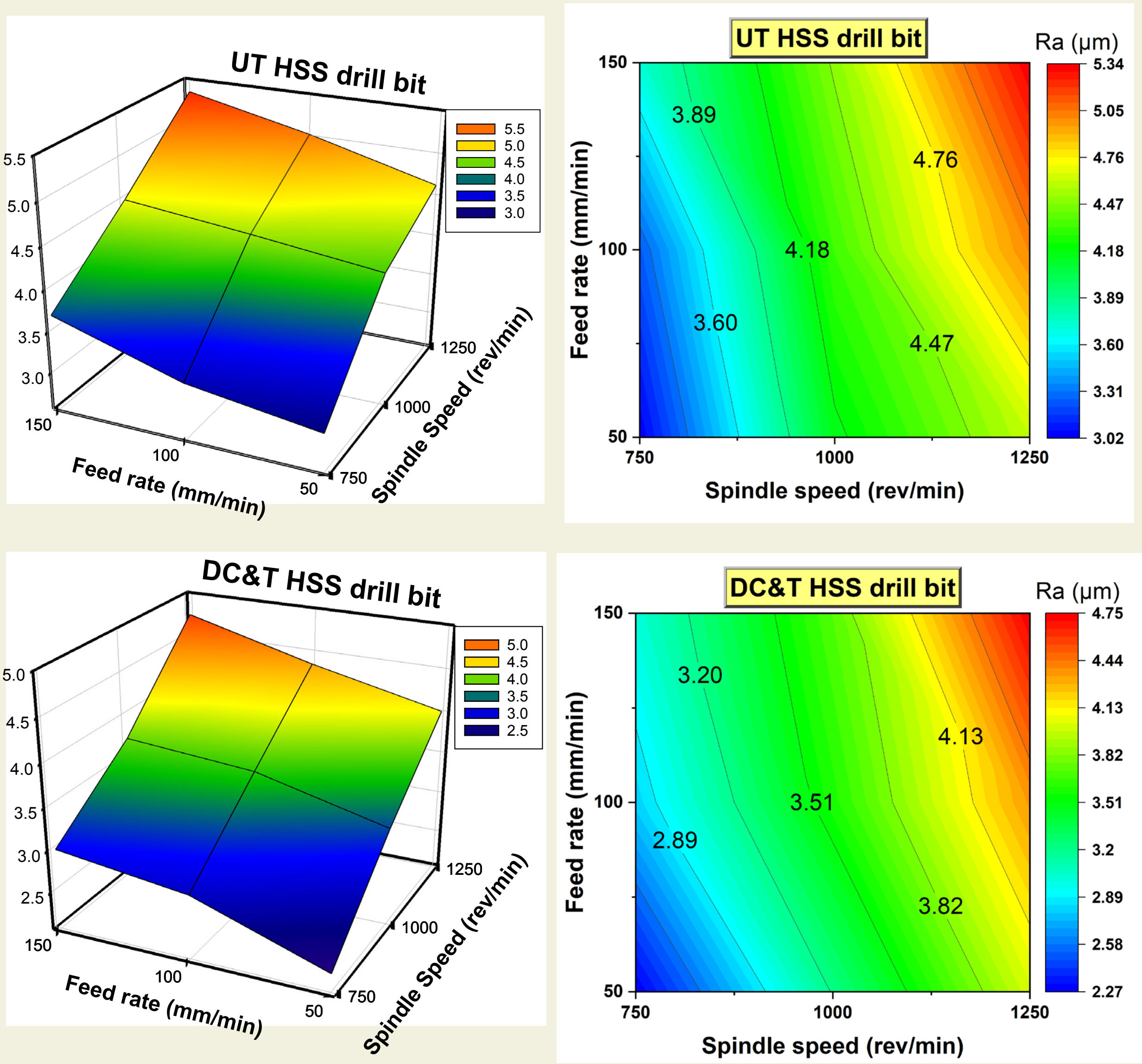


Figure 9. Effects of drilling parameters and levels on Ra

also seen in both UT and DC&T HSS drills. In the light of these results (based on cutting parameters), it seems possible to suggest low spindle speed and low feed rate for the high quality of the holes drilled in the aluminium workpiece used in this study.

On the other hand, as seen in Figure 9, when DC&T and UT HSS drills are compared, it is clearly seen that Ra values are worse with UT HSS drills. In other words, it is clearly understood that performance increase is achieved thanks to DC&T processes applied to HSS drill.

Analysis of S/N ratios for Ra

It was mentioned above (in Taguchi Experiment Design section) that Taguchi experimental design was used in this study. As is known, the noise and signal terms used in Taguchi method are specified as expected (mean) and undesired (standard deviation (SD)) values. In other words, the signal to noise (S/N) ratio is expressed as expected (mean)/undesired (SD). This ratio represents the quality characteristics that deviate from the desired value. For each factor, the highest S/N ratio represents the lowest Ra value. The lowest Ra value also means the best result [46-48]. In this study, the "The smaller the better" (equation 1) approach was used since the lowest Ra value was targeted.

In Figure 10, the S/N ratios obtained as a result of the analysis of Ra values measured from all holes is depicted. The highest S/N ratios calculated according to Ra values of holes drilled on aluminium workpieces using DC&T and UT HSS drills were found to be -7.12 dB (2.27 µm) and -9.62 dB (3.03 µm), respectively. When S/N ratios given in Figure 10 were inspected, it was seen that the results obtained with the DC&T HSS drill were higher.

The main effects plot obtained according to the drilling parameters and levels are depicted in Figure 11. As seen in Figure 11, it is clear that DC&T HSS drill is better for optimum machining. In addition, it is understood that 750 rev/min spindle speed and 50 mm/min feed rate are the most optimum cutting parameters for the aluminium workpiece used in the study.

Analysis of the variance (ANOVA) for Ra

In this study, ANOVA analysis was also performed in order to better understand the effects of experimental design parameters. With this analysis, the interactions of the factors, their significance and the suitability of the model are determined. Thanks to ANOVA analysis, it is understood whether the control factors and their interactions are significant. The main criterion here is that the P-Value of each factor is less than 0.05. If the P-Value is less than 0.05, it means it is significant [27, 49-52]. The results of ANOVA analysis performed according to Ra values obtained within the scope of this experimental study are given in Table 2.

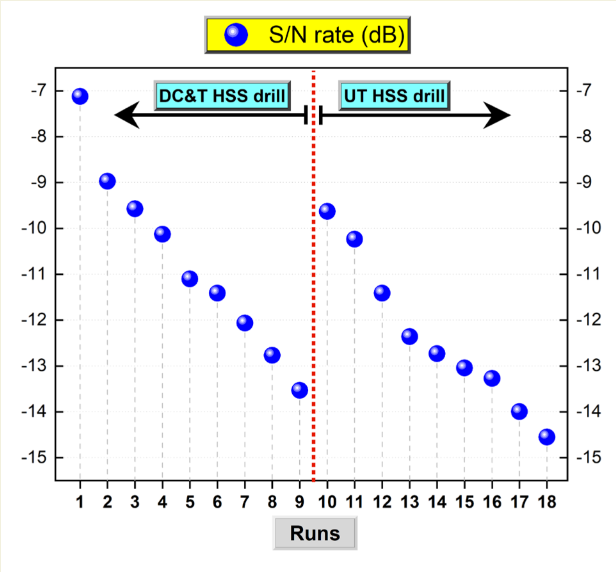


Figure 10. S/N ratios obtained for all Ra values

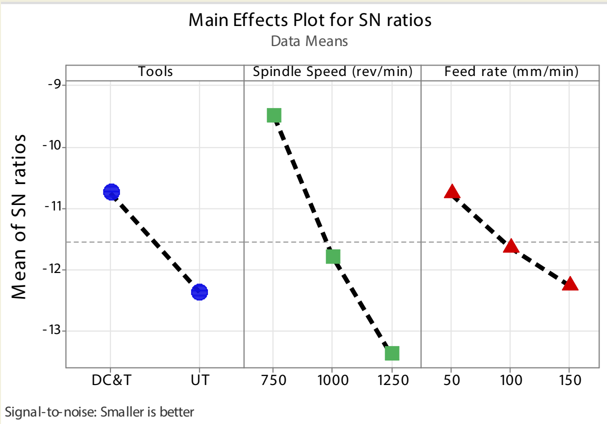


Figure 11. Main effects plot for drilling parameters and levels

When ANOVA results in Table 2 are investigated, it is found that all P-Value values are less than 0.05. From these results, it was revealed that the control factors and their interactions were significant [48]. Figure 12 depicts the percentage contribution values obtained as a result of ANOVA analysis.

As seen in Figure 12, as a result of the ANOVA analysis, the most effective parameters on Ra values were found to be spindle speed (70.62%), tools (18.19%) and feed rate (9.98%), respectively. In the light of the obtained ANOVA analysis results, it was understood that the spindle speed affected Ra value the most. This revealed that it is the most important factor to be considered during the machining of the aluminium workpiece used in this study.

Analysis of the regression for Ra

In this experimental and statistical research, regression equations were also developed with the help of regression analyses. Regression analysis is known for its well-developed statistical theory and elegant underlying mathematics. Regression analysis has many application areas such as engineering, physics, chemistry and economics. Therefore, this statistical method is used extensively [53]. The purpose of the regression analysis used in this research is to obtain equations by analysing the correlation between the drilling parameters and the responses [27,

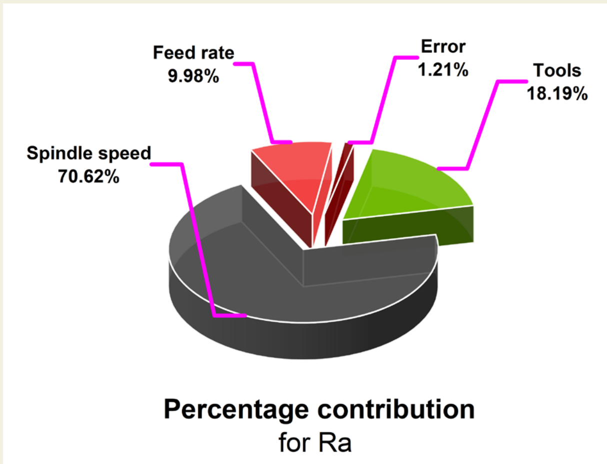


Figure 12. Percentage contribution for Ra

Table 2. ANOVA analysis results for Ra values

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Tools	1	2.1424	18.19%	2.1424	2.14245	180.73	0.00000001351
Spindle Speed	2	8.3187	70.62%	8.3187	4.15936	350.86	0.00000000002
Feed rate	2	1.1757	9.98%	1.1757	0.58784	49.59	0.00000158145
Error	12	0.1423	1.21%	0.1423	0.01185		
Total	17	11.7791	100.00%				

Table 3. Regression equations

Tools			Estimated linear equations
DC&T	Ra (µm)	=	- 0.427 + 0.003327 Spindle Speed (rev/min) + 0.006250 Feed rate (mm/min)
UT	Ra (µm)	=	0.263 + 0.003327 Spindle Speed (rev/min) + 0.006250 Feed rate (mm/min)
R-sq = 98.30			

53]. The linear equations obtained separately for DC&T and UT HSS drills are given in Table 3. When the regression equations in Table 3 are compared, it can be seen that better Ra values can be achieved with the equation developed for DC&T HSS drill.

R^2 (regression coefficient) value was used to show the effectiveness of the model obtained as a result of the regression analysis. As seen in Table 3, R^2 value obtained for Ra values within the scope of this study was 98.30%. The result of this high R^2 value shows that the model developed is quite successful in estimating Ra values. For R^2 values obtained in this context, the success criterion is expressed as 90% and above [39, 53].

Figure 13 depicts the comparison of the predicted Ra values with the experimental Ra results. When the comparison of the predicted and experimental results in Figure 13 is inspected, it is seen that a very good correlation is obtained from the results gathered very close to the regression line. As seen in Figure 13, R^2 (R-sq) value of the quadratic regression model obtained for these comparisons was calculated as 99.8%. Figure 13 also depicts the quadratic regression equation developed for the experimental results and predicted values.

In Figure 14, the predicted Ra values and the experimental Ra results are given separately for DC&T and UT HSS drills, showing the success of the model more clearly. As seen in Figure 14, the powerfully predicted values matched very well with the experimental results. When all these regression results are taken together, it is revealed that the analysis estimates are almost equal to the experimental results, as indicated by R^2 (regression coefficient) value obtained. Therefore, it has been understood that the quadratic regression equation used to calculate the predicted values of Ra is quite successful.

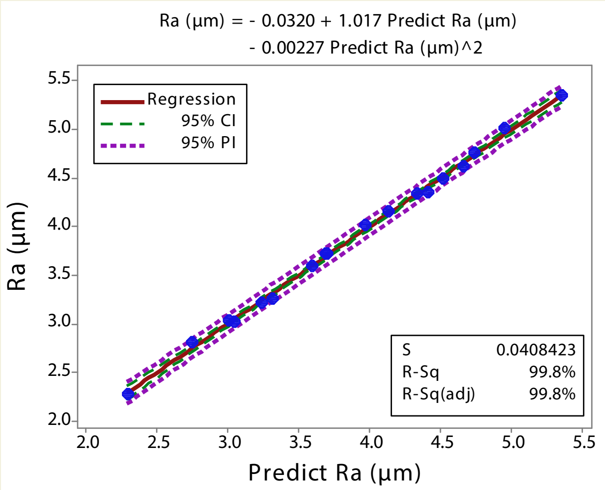
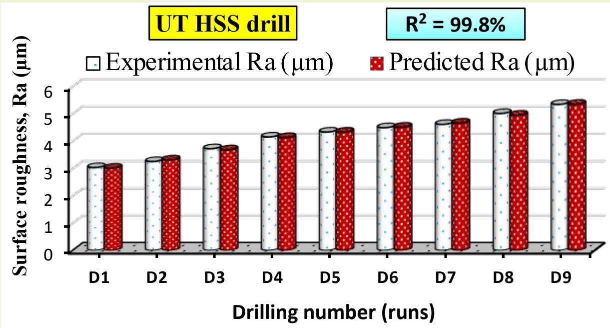
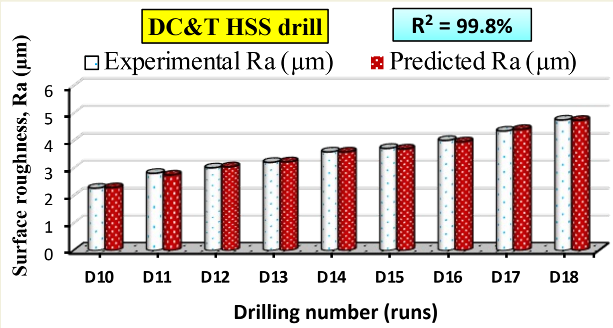


Figure 13. Comparison of predicted values and experimental results for Ra values



(a)



(b)

Figure 14. Predicted vs experimental Ra values for DC&T and UT HSS drills

4. Conclusions

In this experimental and statistical research, the performances of cryo-treated and untreated HSS drills used for drilling AA7075 aluminium alloy workpieces under dry conditions were investigated. The findings and analysis results obtained from investigation are summarized below separately:

- DC&T processes were applied to improve the properties (by modifying the microstructure) of HSS cutting tool.
- Thanks to DC&T processes applied to HSS cutting tool, improvements occurred in its microstructure.
- The hardness value of HSS cutting tool increased by 6.89% with the effect of DC&T processes applied.
- When the highest and lowest Ra values obtained using DC&T and UT HSS cutting tools were compared, it was seen that the DC&T HSS cutting tool performed better by 11.05% and 25.91%, respectively.
- It was observed that the best hole surface quality in

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both DC&T and UT HSS cutting tools was obtained at 750 rev/mm spindle speed and 50 mm/min feed rate parameters. It was determined that the hole surface quality of the aluminium workpiece machined with DC&T and UT HSS drills was negatively affected by the increase in spindle speed and feed rate.

- The highest S/N ratios calculated according to Ra values of holes drilled on aluminium workpieces using DC&T and UT HSS cutting tools were found to be -7.12 dB (2.27 µm) and -9.62 dB (3.03 µm), respectively.

- In ANOVA analysis, since all P-Value values were less than 0.05, it was revealed that the control factors and their interactions were significant, and that the most effective parameters on Ra values were spindle speed (70.62%), tools (18.19%) and feed rate (9.98%), respectively.

- In the regression analysis, R^2 value for Ra values was calculated as 98.30%. The result of this high R^2 value showed that the model developed is quite successful (since the success criterion is 90% and above) in estimating Ra values.

5. Abbreviations

HSS	High speed steel
CT	Cryogenic treatment
SC	Shallow cryogenic treatment
DC	Deep cryogenic process
DC&T	Deep cryogenic treatment and tempering
UT	Untreated
TiN	Titanium nitride
S/N	Signal to noise
OA	Orthogonal array
CNC	computer numerical controlled
Ra	Average surface roughness
SD	Standard deviation
R^2 / (R-sq)	Regression coefficient

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