# The effect of tool material and cutting parameters on the machinability of the supermet 718 nickel-base superalloy

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The objective of the present work is to assess the effect of tool material and cutting parameters on the machinability of the supermet 718 Nickel-base superalloy, under dry cutting conditions and a constant nose radius (0.5 mm). The tool materials used were the ceramic (Sandvik CC680) and the CBN (Sandvik CB50) inserts. These variables were investigated using a $2^k$ factorial design. The present work demonstrates a favorable effect for ceramic inserts on machinability, when compared with CBN inserts. The work also, showed that the feed rate has the dominant effect among the parameters studied on machinability, irrespective of the tool material used.

توصف سبائك النيكل الفوقية بأنها سبائك صعبة التشغيل لما تمتاز به من متانة عالية عند درجات الحرارة المرتفعة/ مقاومة ديناميكية عالية للقص. وعادة ما تستخدم هذه السبائك فى صناعة أجزاء التربينات الغازية والبخارية وأجزاء محركات الطائرات. الهدف من البحث هو دراسة تأثير مادة أداء القطع وظروف القطع على قابلية التشغيل للسبائك الفوقية. فى هذا البحث تم تبنى أسلوب تصميم التجارب بالعوامل لدراسة تأثير مادة أداة القطع (كاربيد – كربون بورون نيتريد) وظروف القطع على قابلية التشغيل لمادة السوبر مت ٧١٨ (أحد سبائك النيكل الفوقية). أظهر البحث تأثير سائد لمعدل التغذية من بين المتغيرات المدروسة على الأسطح المشغلة، بغض النظر عن نوع أداة القطع المستخدمة فى التشغيل. كما أظهر هذا البحث تأثير مفضل لمادة السيراميك على الأسطح المشغلة عند مقارنتها بالكربون بورون نتريد.

**Keywords:** Superalloy, Ceramic inserts, Cubic boron nitride inserts, Factorial design, Material removal rate, Cutting forces.

## 1. Introduction

Properties of the work material have a significant influence on the success of machining operation. These properties and other characteristics of work material are often summarized in terms of machinability. Machinability denotes the relative ease with which a material can be machined to an acceptable surface finish, using the appropriate tooling and cutting conditions. Various criteria are used to evaluate machinability, the most important of which are tool life, forces and power, surface finish and ease of chip disposal [1-5].

In order to meet the demands imposed by increasingly sophisticated designs with durable, but in many cases nearly unmachinable, materials (superalloys) new tools as well as new manufacturing processes (non traditional machining processes) are being developed [1-12].

Nickel-based superalloys are classified as difficult-to-cut materials. The high strengths at high temperatures, high dynamic shear strengths, high work hardening, and low thermal diffusivity, are generally associated with poor machinability of nickel-base superalloys. These aspects lead the tool to high cutting temperature which causes high tool wear. Therefore, ceramic and CBN (Cubic Boron Nitride) tools are recommended for machining the alloys under high cutting speeds [3, 5, 13-16]. Nickel-based superalloys are primarily used in gas and steam turbines and aircraft engine components construction. These alloys resist corrosion from most chemicals and are competitors to stainless steels in the chemical, marine, power equipment, food service, petroleum and paper industry.

Designs to study multiple factors (such as cutting speed, tool material, feed rate, and depth of cut) on a response variable (surface roughness, material removal rates and cutting forces) are considered [12]. Factorial design approaches provide an alternative to studying one factor at a time. They allow the study of interactions between factors. They also allow the data from the experiment to be used to study the effects of each factor. This results in a significant increase in efficiency over studying the factors one at a time [17-21].

The aim of this work, is to implement the factorial design approach to study the effect of tool material and cutting parameters (at constant tool geometry) on the machinability of the supermet 718 nickel superalloy, where different tool inserts namely: CBN (Sandvik CB50) and ceramic (Sandvik CC680) have been used. These variables were investigated using a $2^k$ factorial design.

## 2. Experimental work

### 2.1. Workpiece material

The material used throughout this work was the supermet 718 nickel-base superalloy (0.07% C, 20% Cr. 4.45% Mo. 0.1% Si, 0.1% Mn, 61.03% Ni, 0.75% Fe, 13.5% Co). The workpieces were in the form of cylinders 50 mm in diameter and 500 mm in length. The form of the workpiece is shown in Fig. 1-a. Each step on the workpiece is intended to carryout a specific test condition (see Table 2). This will allow all the cutting tests (16 conditions) to be conducted before removing the test bar. Thus the effect of re-clamping and positioning of the workpieces can be eliminated among the various test conditions.

### 2.2. Tool materials

The cutting inserts (types and geometry recommended by Metal Industries PLC, U.K.) used throughout the present work were CBN (Sandvik CB50) and ceramic (Sandvik CC 680) tool bit inserts. These cutting inserts were geometrically identical, having zero rake angle and 5° clearance angle on the main cutting edge. In order to eliminate the effect of cutting and approach angles on the test results, a fresh cutting insert was used to conduct each cutting test condition.

### 2.3 Cutting test procedure

The process utilized for testing the machinability was a turning operation, performed on a 10 kW SSSR (Russian made) engine lathe model 16k25 with normal accuracy. The cutting tests were conducted under dry conditions and constant nose radius (0.5 mm). Each test bar was placed between three jaws chuck and the tail stock of the lathe. The test bar was not removed until the different cutting tests (16 different conditions, as shown in Table 2) have been conducted. The levels of cutting parameters adopted are listed in Table 1.

### 2.4. Surface roughness measurements

The surface roughness was measured using the portable surtronic-10 surface roughness meter. The center line average, $R_a$ (see Fig. 1-b), was taken to represent the particular test combination, and a cut-off value of 0.8 mm was used. In order to eliminate the effect of different clamping on the test result, the test bar was not removed until the different cutting tests have been conducted.

### 2.5. Cutting force measurements

A three components 9257A Kistler dynamometer with special tool holder, connected to a 5001 SN three channel Kistler charge amplifier was used for measuring the cutting force components, of the present work. It is worth mentioning that before running the cutting test, the Kistler dynamometer was calibrated on an Instron testing machine using a dummy tool, where the gain of the amplifier was adjusted at one volt for each one thousand Newton.

Table 1. Levels of independent variables and coding identification.

| Level | Low | High |
|---|---|---|
| Coding | -1 | +1 |
| Speed "S" (m/min) | 32 | 125 |
| High feed (mm/rev) | 0.15 | 0.6 |
| Low feed (mm/rev) | 0.075 | 0.3 |
| Depth of cut "D" (mm) | 0.5 | 2 |

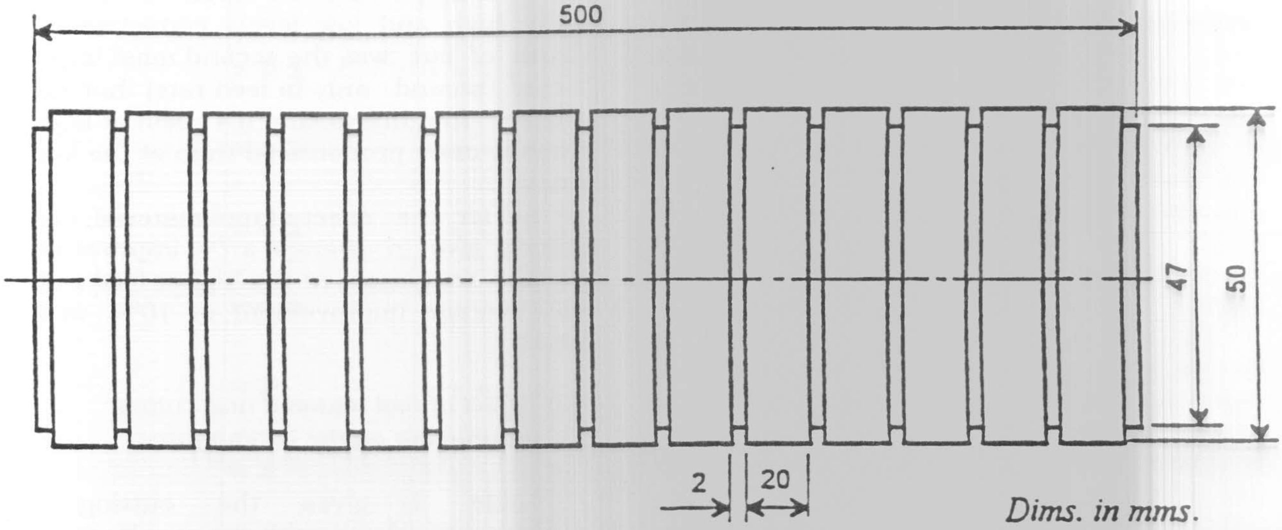
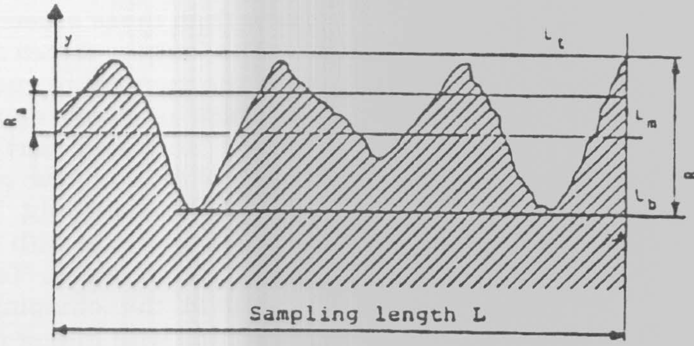


Fig. 1-a. The configuration and dimensions of the machined workpiece.



$L_m$ = Center line (the sum of the areas above = the sum of the areas below)

$L_t$ = Top line (parallel to $L_m$ through the highest point)

$L_b$ = Bottom line (parallel to $L_m$ through the lowest point)

$R_{max}$ = The distance between $L_t$ and $L_b$ (in μm = 0.001 mm)

$$R_a = \frac{1}{L}\int_0^L |y|\, dl \quad \text{(measured in μm = 0.001 mm)}$$

Fig. 1-b. The configuration and dimensions of the machined workpiece

## 3. Factorial design and design matrix

Full factorial design consists of all possible combinations of the factors and their levels was considered. In the present work a $2^k$ factorial design is adopted, where each factor in the experiment is studied at only two levels. There are several reasons for emphasizing the $2^k$ design, such as a relatively few runs are required, the design is easy to use in sequential experimentation and the data can be processed by using graphical methods.

Two levels of feed rate were considered. A low feed rate (ranges from 0.075 to 0.3 mm/rev) and a high feed rate level (ranges from 0.15 to 0.6 mm/rev). Table 1 demonstrates the factors studied and their levels.

The computation of the effects of the factors and the interactions can be performed using an algorithm based on the extended design matrix [17]. Table 2, illustrates the standard form of a design matrix for a $2^4$ design and the estimated effects, where the order in which the 16 combinations were assembled was randomized using a random permutation table [17]. The columns corresponding to the various interactions were obtained by multiplying the signs for the factors contained in the interactions.

Each of the effects is estimated by adding or subtracting the value of the response variable, depending on whether the sign of the appropriate column is plus or minus. Fig. 2 shows the effect of factors and their interactions on the surface roughness. From Fig. 2, it can be seen that the feed rate has the dominant effect on surface roughness. At high feed rates the depth of cut appears to have also an effect on surface roughness.

## 4. Results and discussion

### *4.1. Effect of tool material and cutting parameters on surface roughness*

The paired comparisons are plotted in Figs. 3-6. Where, the solid line represents the high level of the factor (+), and the dashed line represents the low level of the factor (-), as indicated in Table 1. For example, the solid line in Fig. 5, represents the high level of the depth of cut, while the dashed line represents the low level of the depth of cut. From these figures, it can be seen that the cutting speed has a little effect on surface roughness, at both low and high feed rates. The feed rate has the major effect on surface roughness, at both high and low levels considered. The depth of cut was the second most important factor (second only to feed rate) that affected surface roughness, and it's effect at high feed rates is more pronounced than at the low feed rates.

As for the effect of tool material, ceramic inserts give in average a 7% improvement of surface roughness at the higher feed rate and an average improvement of 10%, at lower feeds.

### *4.2. Effect of tool material and cutting parameters on the cutting force*

Table 3 gives the cutting force components along with the resultant cutting force associated with different cutting conditions at high and low feed rates. The table indicates that the cutting forces associated with ceramic inserts are always lower than those associated with CBN inserts.

The cutting forces are normally decreased with the increase in cutting speed. (This drop in forces is partly caused by a decrease in contact area and partly by a drop in shear strength in the flow zone as its temperature rises with increasing speed). However, they seem to increase with the increase in cutting speed as shown in Table 3. This may be related to the chipping of the cutting inserts associated with higher cutting speeds.

### *4.2.1. Paired comparison (tool material)*

Table 3 shows the average resultant cutting forces obtained with the different insert types. The $j^{th}$ paired different is computed as follows:

$d_j = y_{1j} - y_{2j}$ $\quad j = 1, 2,..., 8$

$\mu_d = \mu_1 - \mu_2$

Testing $\mu H_0 : \mu_d = 0$

$H_1 : \mu_d \neq 0$

Table 2. Design matrix for machining the Nickel superalloy.

| Test | Run order | S $F_1$ | F $F_2$ | D $F_3$ | M $F_4$ | S F | S D | S M | F D | F M | D M | S F D | S F M | S D M | F D M | S F D M | Response | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | High Ra (μ.m) | Low Ra (μ.m) |
| 1 | 1 | - | - | - | - | + | + | + | + | + | + | - | - | - | - | + | 0.83 | 0.78 |
| 2 | 12 | + | - | - | - | - | - | - | + | + | + | + | + | + | - | - | 0.69 | 0.76 |
| 3 | 14 | - | + | - | - | - | + | + | - | - | + | + | + | - | + | - | 1.45 | 1.24 |
| 4 | 10 | + | + | - | - | + | - | - | - | - | + | - | - | + | + | + | 1.45 | 1.24 |
| 5 | 8 | - | - | + | - | + | - | + | - | + | - | + | - | + | + | - | 1.04 | 0.89 |
| 6 | 7 | + | - | + | - | - | + | - | - | + | - | - | + | - | + | + | 1.01 | 0.9 |
| 7 | 13 | - | + | + | - | - | - | + | + | - | - | - | + | + | - | + | 1.5 | 1.38 |
| 8 | 3 | + | + | + | - | + | + | - | + | - | - | + | - | - | - | - | 1.5 | 1.28 |
| 9 | 15 | - | - | - | + | + | + | - | + | - | - | - | + | + | + | - | 0.78 | 0.67 |
| 10 | 9 | + | - | - | + | - | - | + | + | - | - | + | - | - | + | + | 0.71 | 0.63 |
| 11 | 5 | - | + | - | + | - | + | - | - | + | - | + | - | + | - | + | 1.32 | 1.2 |
| 12 | 4 | + | + | - | + | + | - | + | - | + | - | - | + | - | - | - | 1.32 | 1.2 |
| 13 | 6 | - | - | + | + | + | - | - | - | - | + | + | + | - | - | + | 0.91 | 0.78 |
| 14 | 16 | + | - | + | + | - | + | + | - | - | + | - | - | + | - | - | 0.89 | 0.69 |
| 15 | 11 | - | + | + | + | - | - | - | + | + | + | - | - | - | + | - | 1.45 | 1.25 |
| 16 | 2 | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | 1.45 | 1.17 |

S = Cutting speed
F = Feed rate
D = Depth of cut
M = Tool material

**Table 3.** Data for the cutting forces testing experiment.

| Exp. No. | Cutting Conditions | | | Cutting Forces | | | | | | | | Paired Comparison | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | CBN | | | | Ceramic | | | | | | |
| | V rp.m | f mm/rev | d mm | $F_c$ | $F_f$ | $F_r$ | R ($Y_{1j}$) | $F_c$ | $F_f$ | $F_r$ | R ($Y_{2j}$) | | Difference (dj) | Difference $(dj)^2$ |
| 1 | 200 | 0.15 | 0.5 | 673 | 230 | 170 | 732 | 559 | 207 | 157 | 617 | High Feeds | 115 | 13225 |
| 2 | 800 | 0.15 | 0.5 | 880 | 370 | 290 | 998 | 830 | 330 | 251 | 928 | | 70 | 4900 |
| 3 | 200 | 0.6 | 0.5 | 2260 | 850 | 653 | 2502 | 2236 | 826 | 629 | 2467 | | 35 | 1225 |
| 4 | 800 | 0.6 | 0.5 | 2641 | 1290 | 1091 | 3136 | 2600 | 1265 | 1065 | 3080 | | 56 | 3136 |
| 5 | 200 | 0.15 | 2 | 1326 | 493 | 383 | 1466 | 1290 | 478 | 363 | 1423 | | 43 | 1849 |
| 6 | 800 | 0.15 | 2 | 1637 | 670 | 551 | 1853 | 1600 | 630 | 520 | 1797 | | 56 | 3136 |
| 7 | 200 | 0.6 | 2 | 3670 | 1490 | 1187 | 4135 | 3630 | 1450 | 1150 | 4075 | | 60 | 3600 |
| 8 | 800 | 0.6 | 2 | 4037 | 1593 | 1330 | 4540 | 4000 | 1550 | 1290 | 4480 | | 60 | 3600 |
| | | | | | | | | | | | | | $\sum_{i=1}^{n} (d_j) = 495$ | $\sum_{i=1}^{n} (d_j)^2 = 34671$ |
| 9 | 200 | 0.075 | 0.5 | 343 | 142 | 125 | 392 | 301 | 113 | 89 | 333 | Low Feeds | 59 | 3481 |
| 10 | 800 | 0.075 | 0.5 | 500 | 230 | 195 | 584 | 487 | 198 | 150 | 547 | | 37 | 1369 |
| 11 | 200 | 0.3 | 0.5 | 1200 | 500 | 382 | 1355 | 1182 | 470 | 356 | 1321 | | 34 | 1156 |
| 12 | 800 | 0.3 | 0.5 | 1470 | 796 | 630 | 1787 | 1431 | 760 | 590 | 1725 | | 62 | 3844 |
| 13 | 200 | 0.075 | 2 | 710 | 300 | 251 | 811 | 682 | 270 | 203 | 761 | | 50 | 2500 |
| 14 | 800 | 0.075 | 2 | 872 | 366 | 300 | 993 | 831 | 335 | 270 | 936 | | 57 | 3249 |
| 15 | 200 | 0.3 | 2 | 2346 | 1150 | 870 | 2754 | 2313 | 1100 | 830 | 2693 | | 61 | 3721 |
| 16 | 800 | 0.3 | 2 | 2660 | 1340 | 1077 | 3168 | 2610 | 1290 | 1055 | 3097 | | 71 | 5041 |
| | | | | | | | | | | | | | $\sum_{i=1}^{n} (d_j) = 431$ | $\sum_{i=1}^{n} (d_j)^2 = 24361$ |

$F_c$ = Tangential force $F_f$ = Feed force $F_r$ = Radial force

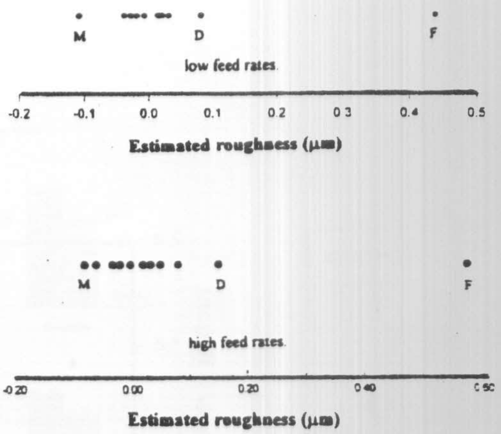


Fig. 2. Effects of factors on surface roughness.

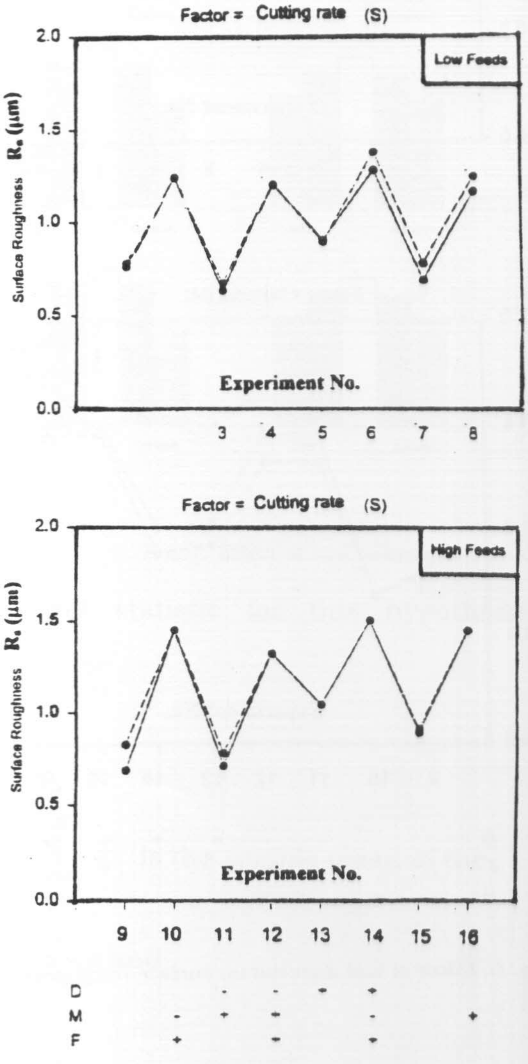


Fig. 3. Effect of cutting speed on surface roughness.

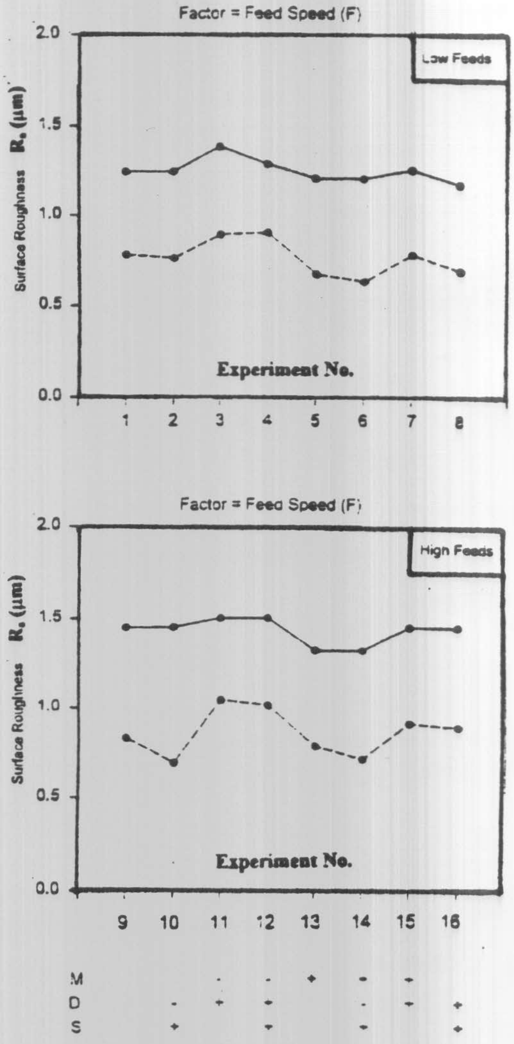


Fig. 4. Effect of feed rate on surface roughness.

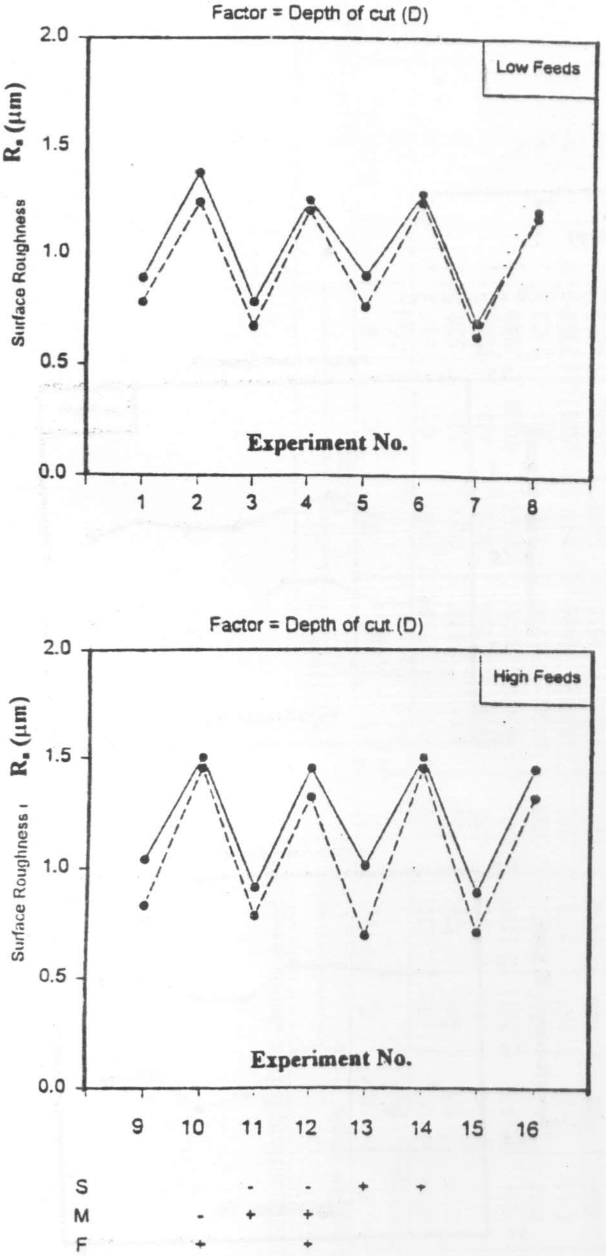


Fig. 5. Effect of depth of cut on surface Roughness.

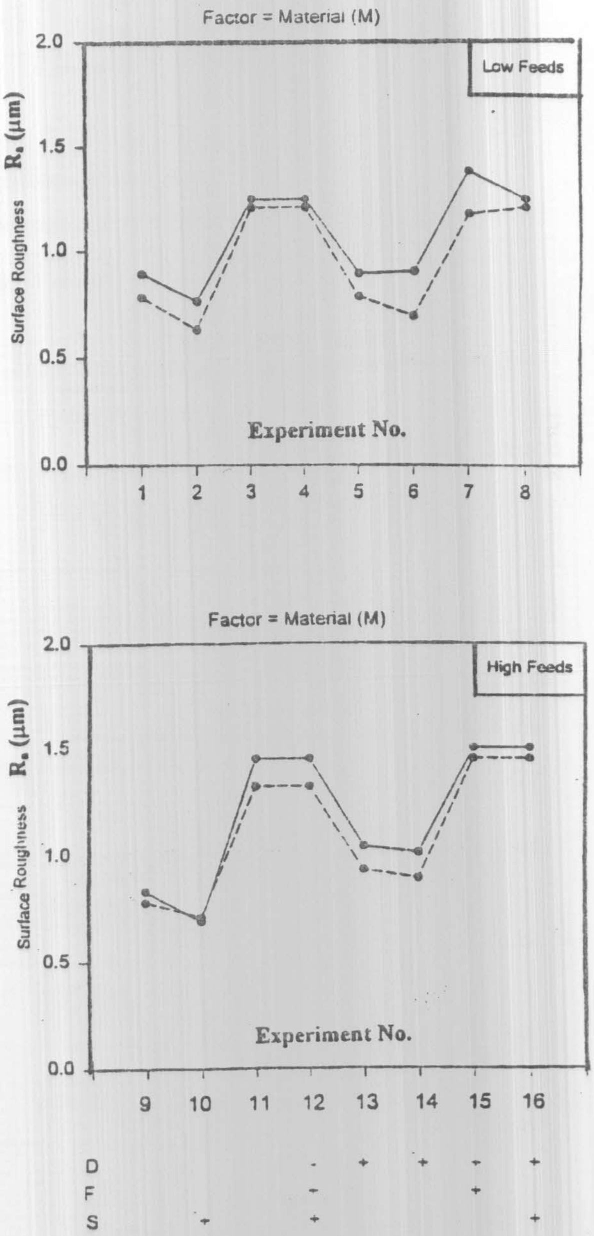


Fig. 6. Effect of tool material on surface roughness.

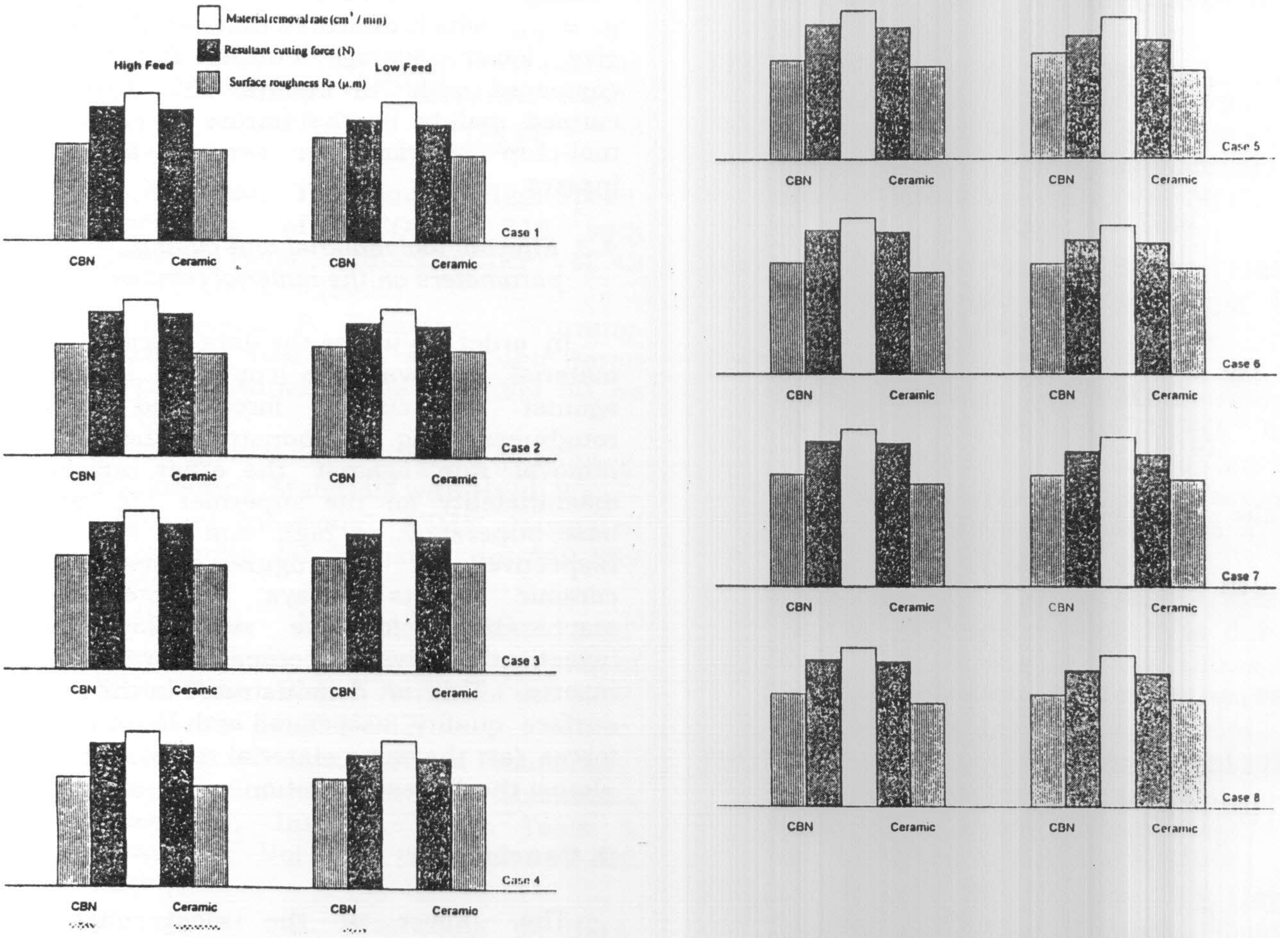


Fig. 7. Effect of tool material on cutting performance at different material removal rates.

the test statistic for this hypothesis is

$$t_0 = \frac{\bar{d}}{S_d/\sqrt{n}},$$

where,

$\bar{d} = \frac{1}{n}\sum_{i=1}^{n} d_j$ is the sample mean of the differences and

$$S_d = \left[\frac{\sum_{j=1}^{n} d_j^2 - \frac{1}{n}\left(\sum_{j=1}^{n} d_j\right)^2}{n-1}\right]^{\frac{1}{2}},$$

is the sample standard deviation of the differences.

$H_0 : \mu_d = 0$ would be rejected if $|t_0| > t_{\frac{\alpha}{2}, n-1}$.

**For High Feeds**

$$\bar{d} = \frac{1}{8}(495) = 61.875$$

$$S_d = \left[\frac{34671 - \frac{1}{8}(495)^2}{7}\right]^{\frac{1}{2}} = 24.03$$

$$t_0 = \frac{61.875}{24.03/\sqrt{8}} = 7.28$$

Take $\alpha = 0.1$

$$t_{\frac{\alpha}{2}}, n-1 = t_{\frac{0.1}{2}}, 8-1 = t_{0.05}, 7 = 1.895$$

we can reject the hypothesis $H_0 : \mu_d = 0$

**For Low Feeds**

$$\bar{d} = \frac{1}{8}(431) = 53.875$$

$$S_d = \left[\frac{24361 - \frac{1}{8}(431)^2}{7}\right]^{1/2} = 12.77$$

$$t_0 = \frac{53.875}{12.77/\sqrt{8}} = 11.95$$

Take $\alpha = 0.1$

$$t_{\frac{\alpha}{2}}, n-1 = t_{\frac{0.1}{2}}, 8-1 = t_{0.05}, 7 = 1.895$$

we can reject the hypothesis $H_0 : \mu_d = 0$

That is, there is an evidence to indicate that the two insert types gave different cutting forces readings. That also mean that $\mu_1 \neq \mu_2$, which indicates that ceramic inserts give lower average cutting forces when compared with CBN inserts. This is probably caused mainly by the nature of contact at tool-chip interface for ceramic and CBN inserts.

### *4.3. Effect of tool material and cutting parameters on the material removal rate*

In order to utilize the data efficiently, the material removal rate (cm$^3$/min) is plotted against the cutting force and surface roughness. Fig. 7 demonstrates the material removal rate against the other indices of machinability for the supermet 718 nickel-base superalloy, at high and low feed rates, respectively. The figure indicates that ceramic inserts always promote higher machinability for the superalloy under investigation; when compared with C.B.N inserts. This is demonstrated in the higher surface quality associated with lower cutting forces (at the same material removal rate), in almost the 16 test conditions.

## 5. Conclusions

The effect of the most important machining factors on the machinability of the supermet 718 nickel superalloys, was investigated using the $2^k$ factorial design of experiments. The following can be concluded from the present investigation:

1. Ceramic inserts demonstrated a favorable effect, on machinability when compared with CBN inserts, at both high and low feed rates.
2. The feed rate has the dominant effect among the parameters studied, on the machinability of the supermet 718 nickel-base superalloy under investigation.
3. The depth of cut is the second factor (second only to feed rate) that affected machinability. Also, the effect of depth of cut at high feed rates is more pronounced than its effect at low feed rates.

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