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DIMENSIONAL INSTABILITY STUDIES IN MACHINING OF INCONEL 718 NICKEL BASED SUPERALLOYS AS APPLIED TO AEROGAS TURBINE COMPONENTS

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ABSTRACT

Inconel 718 alloy is used extensively in aerogas turbines and this alloy is most difficult to machine and highly prone to dimensional instability after machining. Such detrimental phenomenon poses enormous problem in engine assembly and affect structural integrity. This paper highlights the systematic research work undertaken to study the plastic deformation characteristics of Inconel 718, effect of process variables on machined surface, subsurface and dimensional instability. Also illustrated the technique developed for simultaneous optimization of several process variables such as cutting speed, feed, depth of cut, rake angle and tool nose radius, to control the residual stresses and dimensional instability, within the acceptable tolerance band of the component. Prediction equations were developed for residual stress, dimensional instability, tool life, surface finish and material removal rate. Predicted data were validated experimentally. This paper also presents the qualitative and quantitative data on dimensional instability with specific case studies of jet engine components and clearly illustrates the approach followed to develop technique to control such detrimental effect.

1 INTRODUCTION

The dimensional instability phenomenon is basically a change in dimension with respect to time without doing any further work on it. Two probable causes for dimensional instability have been identified. They are residual stresses and metallurgical alterations introduced by the machining processes. The primary and secondary machining process leads to surface layer changes such as series of metallurgical changes, plastic deformation and residual stresses, etc. which effect the surface integrity and results into dimensional instability of finished part. The magnitude of the residual stresses and metallurgical alterations introduced during the machining process depends on the machinability parameters like speed, feed, depth of cut, cutting tool material and geometry, cutting fluid, etc. Normal industry practice is to carry out the thermal stress relieving process to reduce the effect of residual stresses on dimensional instability at finish machining stage.

The thermal stress relieving process, is not suppose to change the properties or hardness of material but unfortunately there is no stress reliving cycle for Inconel 718 alloy other than following solutionizing process, which will change the properties and hardness. Also only limited aging process is permitted on this material to avoid alloy degradation. This metallurgical restriction compels to control the residual stress by controlling the machinability parameters, which are the influencing factors for the introduction of residual stress. Therefore the dimensional instability could be controlled by better understanding the metallurgy of Inconel 718, the plastic deformation characteristics of Inconel 718, effect of process variables on machined surface and subsurface and finally by controlling machinability parameters. Two aspects of the studies related to dimensional instability

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NOMENCLATURE

α =	rake angle, deg.
d =	depth of cut, mm
d_i =	desirability of response variable
$DIMI$ =	dimensional instability, µm
f =	feed, mm/rev
ID =	inner diameter, mm
MRR =	metal removal rate, mm³/min
OD =	outer diameter, mm
r =	tool nose radius, mm
R_a =	surface roughness, µm
σ_c =	circumferential residual stress, MPa
σ_l =	longitudinal residual stress, MPa
T =	tool life, min
v =	cutting speed, m/min
y =	variable representing response variables
y_c =	central value of response variable

Subscripts

max =	indicating maximum value
min =	indicating minimum value

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have been presented here. First is the plastic deformation characteristics of Inconel 718 and effect of process variables on machined surface and dimensional instability, second one is simultaneous optimization of various process parameters to control the dimensional instability

A few studies on dimensional instability have been reported in the literature. Marschall and Maringer[1] have reported the various aspects of dimensional instability. According to them the major causes for a dimensional instability are the residual stress effects and metallurgical alteration. Isreli and Bendeck[2] have reported the instability parameters for machined. parts. They also emphasized the effect of residual stress distribution on dimensional instability. They defined the specific instability potential as parameter for specifying process operations. Komanduri, et al.[3] reported that highly localized shear stress/strain and temperature in machining of Inconel 718 alloy produces the shear instability. Whereas Marschall[4] and Meyerson, et al.[5] have studied the general effect of micro structural changes on dimensional instability. Although they have not made any specific study on Inconel 718 alloys but they have emphasized the various mechanismby which material may undergo dimensional changes as a result of internal changes at micro structural level. Few more researchers[6-7] have also reported the dimensional instability effect due to residual stress during the machining on conventional steel but not on Inconel 718 superalloys. Subhas, et al.[8] reported dimensional instability phenomenon on titanium alloys but not on Inconel 718. The studies conducted by Subhas[12] on other nickel based superalloys like Nimonic-90, Inconel 901 reveals that there is no appreciable dimensional instability phenomenon, on these alloys. The literature review indicates that no systematic comprehensive studies have been reported on dimensional instability phenomenon of Inconel 718 alloy. The present investigation work is therefore planned to study the plastic deformation characteristics of Inconel 718, effect of process variables on machined surface and dimensional instability in machined jet engine components.

Second part of the study relates to optimization of machinability parameters to control the dimensional instability. Most of the studies reported on machinability parameters optimization are limited to speed, feed, depth of cut by varying one parameter at a time with optimization criteria of maximum production rate and minimum cost. They generally followed Taylor's tool life equation for optimization. These methods do not consider the inter related effect of machinability parameters and are likely to be error prone. Jose, et al.[10] and others[11-17] used statistical method for design of experiment and optimization. This method considerably reduces the number of experiment and statistically accurate. Wu[11] applied response surface methodology for optimization of tool life. He fitted first and second order equation and tested for adequacy, where as Albuelenga, et al.[12] developed mathematical models representing metal cutting operations. Similarly, Shin, et al.[13] presented model for optimization of machining conditions. Optimization problem formulated by them is multi-variable non linear programming problems where as Prasad, et al.[14] used combination of geometric and linear programming technique. No data are reported to the knowledge of the authors on simultaneous optimization of all machining process parameters along with response functions especially with criteria of least residual stress and dimensional instability for application to aerogas turbine components. Although Edwin, et al.[15] and George Derringer, et al.[16] presented an approach of desirability function and simultaneous optimization for rubber industry application, such approach is not followed for machining parameter optimization. Therefore a simultaneous optimization technique is developed in this study to generate qualitative and quantitative data on optimum machinability parameters with criteria of least residual stress and dimensional instability as applied to aerogas turbine components.

2 VALIDATION OF DIMENSIONAL INSTABILITY PHENOMENON

Although dimensional instability was experienced extensively on jet engine components like compressor disc as shown in Fig.1, for better understanding and to validate existence of dimensional instability problem, experimental studies were carried out by machining the ring type specimen made of Inconel 718 alloy in fully heat treated condition

Similar test specimen were machined out of

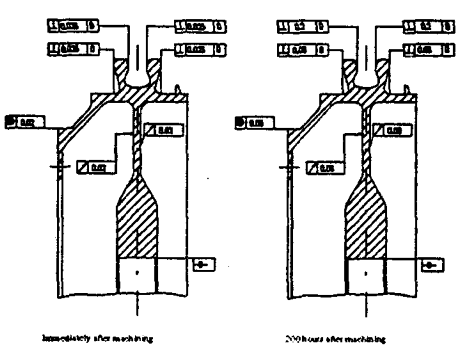

Fig.1 Dimensional instability in IV stage compressor disc

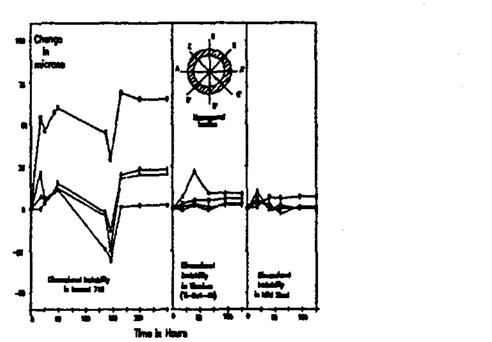

Fig.2 Dimensional instability of Inconel 718, titanium alloy and mild steel

titanium(Ti-6Al-4V) alloy and mild steel at identical machining conditions of Inconel 718 specimen and dimensional changes were measured with respect to time upto 220 hours after machining, the test results are presented in graphical form in Fig.2.

Traditionally titanium alloys are more prone to dimensional instability due to low modulus of elasticity, where as the experimental values show that Inconel 718 is more prone to dimensional instability than titanium alloy but this phenomenon was not noticed in other nickel based alloys. This experiment validates the existence of dimensional instability effect of Inconel 718.

3 INVESTIGATION ON PLASTIC DEFORMATION CHARACTERISTICS

The literature review clearly indicates that further investigations are required on deformation characteristics of Inconel 718, particularly to correlate the metal cutting variables, chip morphology and their effect on structural phase transformation, residual stress and dimensional instability. Therefore experimental studies were carried out to investigate the following aspects of plastic deformation characteristics.

(a) Effect of machinability parameters on chip morphology.

(b) Effect of cutting variables such as length of shear plane, tool geometry, etc. on pattern of residual stress.

(c) Effect of direct machinability parameters on plastic deformation and resulting residual stresses.

3.1 Experimental setup and Procedure

Experimental procedure involved in the present work is of two fold. Machining experiments and hole drilling strain gauge experiment for determining the residual stresses.

3.1.1 Machining Experiment Machining experiments are carried out to study the effect of machinability parameters on plastic deformation characteristics. The ring type Inconel 718 specimen machined to ID 55 mm and OD 76 mm, stress relieved and aged to hardness 44 HRC was selected for machining experiment. The machining experiments were carried out on horizontal lathe, to avoid clamping pressure the specimen was held in mandrel. Kennametal brazed type carbide tools of K-68 grade ground to suitable tool geometry are used in machining experiments. The cutting fluid used is soluble oil(1:20) For every set of cutting parameters chips were collected. Optical micro graph of machined surface and longitudinal mid section of the chips were taken. The dimensions of the specimen were measured on OD at predetermined distance on Mauser 3D co-ordinate measuring machine. The dimensional instability is determined by taking measurements immediately after machining and after 200 hours or more. Tool flank wear and contact length at chip-tool interface are measured using a tool maker's microscope. A portable perthometer is used to measure the surface finish. Cutting forces were measured using Kistler 3 component tool force dynamometer.

3.1.2 Hole Drilling Strain Gauge Experiment

The experiment is carried out a per ASTM standard test method E 837[17]. A special three element strain gauge rosette, Measurement Group type A06-062RE-120 is installed on the machined surface of test piece at the point where residual stresses are to be determined. The three gauge grids are wired and connected to static strain indicator P-3000 thorough a switch and balance unit SB-10 of Measurement Group Inc., USA. A precision milling guide model RS-200 is attached to the test part and accurately centered over drilling target on the rosette. After zero balancing the gage circuits, a small shallow hole is drilled through the center of the rosette using a carbide cutter, run by high speed air turbine unit. Relaxed strains are read for each predetermined incremental depth. The experimental set up and the close-up view of the gauge installed on the specimen are shown in Fig.3 and Fig.4.

3.2 Results and Discussion

Optical microscopic examination of the longitudinal mid section of chips produced at various speeds ranging from 10 m/min to 38 m/min show that there is a considerable deformation twinning. In Fig.5 twinning can be seen in the deformed regions of Inconel 718 chips. Fig.6 also show that even on the machined surface deformation twinning is noticed. This kind of deformation twinning is not generally the prevalent mode of machining of other conventional steels and high temperature alloys[3]. Komanduri et al.[3] also observed similar phenomenon when Inconel 718 machined at cutting speed of 100 m/min and titanium alloy machined upto 260 m/min. Their comparative studies of shear instability in machining of Inconel 718 and Ti-6Al-4V alloy show that role of limited slip in the case of Ti-6Al-4V alloy can be considered to that of precipitates in Inconel 718. The higher resistance to deformation of Inconel 718 probably balances the slightly poor thermal properties of Ti-6Al-4V alloy. An h.c.p. structure titanium alloy provides limited slip and a f.c.c. structure material strengthened by precipitation phase(b.c.t.) such as Inconel 718 resist deformation upto high temperature. The experimental results show that shear localized chips formed with Inconel 718 were similar to the chips generated with titanium Ti-6Al-4V alloy[3].

The analysis of experimental results confirms that the primary deformation process of Inconel 718 is similar to titanium alloy, therefore Inconel 718 also behaves similar way to titanium alloys in dimensional instability. However, the experimental results presented in Fig.1 shows that magnitude of dimensional instability is more in Inconel 718 than titanium. This may be attributed to the presence of γ'' phase in Inconel 718, whereas similar phenomenon was not noticed in other nickel based superalloys, like Nimonic-90, Inconel-901 which are not precipitate strengthened with presence of γ" phase. This is very interesting observation resulted from this experimental investigation and analysis.

The analysis of experimental results related to studies on influence of machinability parameters on plastic deformation mechanism and resulting residual stresses, gives very interesting findings, which are discussed here. Fig.7 shows experimental results on the effect of rake angle on residual stresses. The negative rake angle increases the residual stress and positive rake angle decreases the residual stress. These observed phenomenon are logically correct because as the rake angle increases, shear angle increases, shear plane length decreases, cutting force decreases, shear stress and strain decreases. Thus the residual stresses decreases. These observations are further strengthened from experimental resultspresented in Fig.8. The experiential results shown in Fig.9 indicates that as the chip tool contact length decreases the cutting forces decrease, that is, reduction in chip tool contact length reduces the plastic strains and the residual stresses. Fig.10 and Fig.11 show the residual stress distribution for two different sets of cutting parameters. It is shown that the greater the distance from the machined surface, the lesser the amount of plastic deformation that occurs in, thus the lesser the residual stresses are. It is also clear that residual stresses in cutting direction is more tensile than that in the longitudinal direction. This is qualitatively agreement with results reported in [18].

Fig.12 shows the effect of feed on residual stress distributions. At the lower feeds, the surface residual stresses are compressive, but at the higher feeds they are tensile. The results obtained are in consistent with that reported in[18]. The effect of depth of cut on the residual stress distribution is shown in Fig.13 As the depth of cut increases, the volume of material being removed increases, which requires higher cutting energy to be expanded. Therefore the surface residual stresses increased with the depth of cut. The residual stress magnitude is the highest in Fig.10. The cutting parameters used in this case is such that the combined effect of negative rake angle, higher feed rate and depth of cut introduced larger

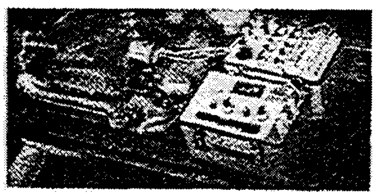

Fig.3 Experimental set up for hole drilling method of residual stress measurement

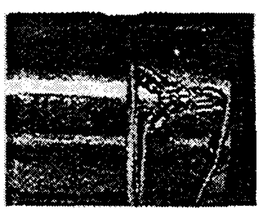

Fig.4 Test specimen with strain gauge rosette mounted on it

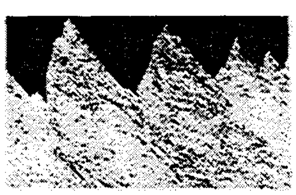

Fig.5 Optical micrograph of longitudinal mid section of the chip(Magnification: 500X)

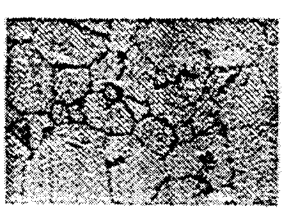

Fig.6 Optical micrograph of machined specimen(Magnification: 500X)

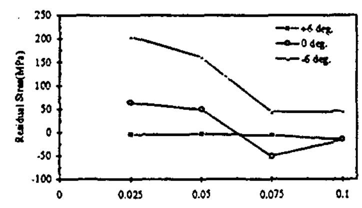

Fig.7 Effect of rake angle on residual stress distribution(v=13m/min, f=0.04 mm/rev, d =0.5 mm)

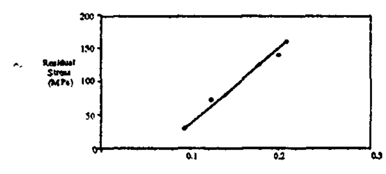

Fig.8 Residual stresses in cutting direction versus shear plane length

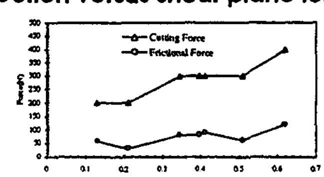

Fig.9 Cutting Force and Frictional force versus Contact length

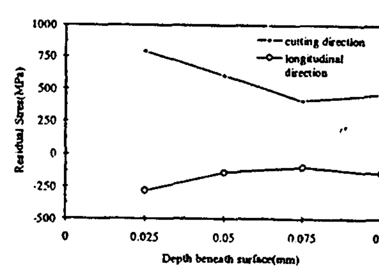

Fig.10 Residual stress distribution
(v=32 m/min, f=0.13 mm/rev, d =1.0 mm, α = -6°)

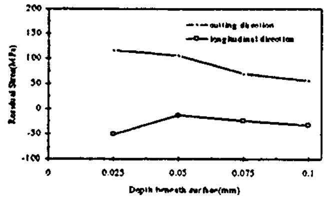

Fig.11 Residual stress distribution
(v=13 m/min, f=0.13 mm/rev, d=1.0 mm, α= +6°)

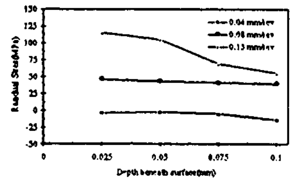

Fig.12 Effect of feed on residual stress distribution(v=13 m/min, d=0.5 mm, α=6°)

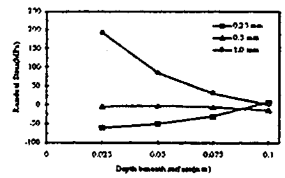

Fig.13 Effect of depth of cut on residual stress distribution(v=14 m/min, f=0.04 mm/rev, α=6°)

Table 1 Recommended range of practical machining conditions

Independent Variables	Maximum (+)	Minimum (-)
v	38	10
f	0.22	0.04
d	1.0	0.25
α	+6	-6
r	1.2	0.4

magnitude of stresses of mechanical origin. In addition to this higher cutting speed introduces stresses of thermal origin due to higher temperatures at the cutting region. This is responsible for the higher magnitude of surface residual stresses.

The investigation studies on plastic deformation aspects of Inconel 718 alloy clearly indicate that direct machinability parameters significantly influences the magnitude of residual stresses and residual stresses are primarily responsible for the dimensional changes hence by optimization of machinability parameters dimensional instability could be controlled. Therefore a new methodology for optimization of machining process has been developed.

4 OPTIMIZATION OF MACHINING PROCESS PARAMETERS

This part of the study is related to the development of process parameter optimization technique to control the dimensional changes within the acceptable limits. An attempt is made to establish the appropriate technique to arrest this dimensional instability and to validate the established techniques experimentally.

4.1 Methodology

The steps involved in the proposed method are as follows

(i) Selection of machining process variables

(ii) Design of statistical experiment

(iii) Determination of predicting equation for the response functions such as residual stresses, tool life surface finish and dimensional instability using response surface methodology and adequacy tests for the predicted equations.

(iv) Computation of optimum machinability parameters such as cutting speed, feed, depth of cut, rake angle and tool noise radius by iterative search method for combination of the responses using desirability function approach.

4.2 Selection of Process Variables

Most of the critical gas turbine components are axisymmetric in geometry, therefore turning process is used in this research work. The turning process variables such as speed, feed, depth of cut, rake angle, tool nose radius, side cutting edge angle, cutting tool material and cutting fluids have varying degrees of influence on the residual stress out of these side cutting edge angle does not have significant influence. Already optimized data are available on selection of cutting fluid as soluble oil(1:20) and cutting tool material as micro grain carbide for machining of nickel based superalloys[9]. Hence these data are chosen form literature. In view of this only five process variables, cutting speed, feed, depth of cut, nose radius and rake angle were chosen for optimization. The maximum and minimum levels were selected taking into account, the recommended range of practical machining conditions used in finish machining of Inconel 718 as shown in Table 1 .

4.3 Design of Statistical Experiment

The present investigation involves the study of the influence of speed, feed, depth of cut, rake angle and tool nose radius on response properties namely residual stress, tool life, surface finish, dimensional instability and material removal rate. Here the influence of process variables on response properties were assumed to be linear and hence it was sufficient to study each variable at two levels only. The main effect of five factors were studied using half factorial design involving only sixteen experiments.

Table 2 Experimental data

Trial No.	υ	f	d	α	r	σ_r	σ_I	R_a	T	$DIMI$
1	10	0.04	0.25	-6	0.4	190	18.5	0.35	11.5	47.0
2	38	0.04	0.25	-6	0.4	220	20.0	0.28	6.0	55.0
3	10	0.22	0.25	-6	0.4	350	31.5	2.40	6.5	87.5
4	10	0.04	1.00	-6	0.4	280	26.0	0.90	11.0	70.0
5	10	0.04	0.25	+6	0.4	40	6.7	0.70	12.0	10.0
6	10	0.04	0.25	-6	1.2	200	19.0	0.30	10.5	50.0
7	38	0.22	0.25	-6	0.4	790	55.3	1.60	4.0	197.5
8	38	0.04	1.00	-6	0.4	300	28.5	0.40	5.0	75.0
9	38	0.04	0.25	+6	0.4	160	15.0	0.25	6.0	40.0
10	38	0.04	0.25	-6	1.2	230	22.5	0.28	5.5	57.5
11	10	0.22	1.00	-6	0.4	400	36.7	3.20	5.5	100.0
12	10	0.22	0.25	+6	0.4	290	27.5	2.00	6.5	72.5
13	10	0.22	0.25	-6	1.2	380	31.7	4.00	5.2	95.0
14	10	0.04	1.00	+6	0.4	100	8.5	0.80	12.0	25.0
15	10	0.04	1.00	-6	1.2	295	28.0	0.85	11.0	73.8
16	10	0.04	0.25	+6	1.2	50	7.7	0.60	12.0	12.5
17	24	0.13	0.625	0	0.8	325	25	1.8	7	80
18	24	0.13	0.625	0	0.8	267	23.9	2.6	8.1	67
19	24	0.13	0.625	0	0.8	290	27	1.2	7.5	82
20	24	0.13	0.625	0	0.8	310	23	1.0	8	65

Experimental Procedure The experimental procedure followed is same as that followed for plastic deformation experiment given in the earlier paragraphs. Experimental data generated are given in Table 2. The trial numbers 17 to 20 are used for checking the adequacy of the predicted equations.

4.4 Prediction Equation for Process Responses

The effect of five independent machining parameters during turning operation on residual stress, tool life dimensional instability, surface finish and material removal rate were established by multiple regression analysis. The equation fitted is a first order with linear functional relationship. The two levels of independent variables are coded for convenience into -1(low) and +1(high) by the transforming equations. Typical transforming equations for the variables are of the following form.

$$\frac{2\upsilon - (\upsilon_{max} + \upsilon_{min})}{(\upsilon_{max} - \upsilon_{min})} \qquad (1)$$

$$\frac{2(\ln\upsilon - \ln\upsilon_{max})}{(\ln\upsilon_{max} - \ln\upsilon_{min})} + 1 \qquad (2)$$

The transforming equation (1) is used for the independent variables when the prediction equations are required in polynomial form and equation (2) is used when the prediction equations are required in exponential form. Similar transformation equations are used for other variables. These transformations were carried out by using a computer program and the following predictions have been derived.

$$\sigma_c = -30.12 + 4.94\upsilon + 1477.34f + 76.23d - 10.55\,\alpha + 2.714r \qquad (3)$$

$$\sigma_I = 2.24 + 0.31\upsilon + 1055f + 6.988d - 0.86\,\alpha + 0.676r \qquad (4)$$

$$T = 9.95\upsilon^{-0.488} f^{-0.353} d^{-0.053} r^{-0.069} (\alpha+7)^{0.022} \qquad (5)$$

$$DIMI = -7.89 + 1.24\upsilon + 370.06f + 19.25d - 2.63\,\alpha + 0.858r \qquad (6)$$

$$R_a = 4.157\,\upsilon^{-0.569} f^{1.52} d^{0.355} r^{0.113} (\alpha+7)^{0.082} \qquad (7)$$

The following standard formula is used for material removal rate,

$$MRR = 1000.\upsilon.f.d \qquad (8)$$

Validity of Prediction Equations These equations are valid when υ, f, d, α and r are within the minimum and maximum levels employed in the experiment as shown in Table 1. These equations were checked for adequacy by analysis of variance. The usual method is to find the ratio of lock of fit mean square to pure error mean square and compare this ratio with F-static. The error mean square is estimated from the repeated tests carried out at the mid point of the machinability range chosen for this study. The tests were repeated four times(Trial No. 17 to 20 in Table 2) and the results are within acceptable range. The fitted equations are found to be adequate since no significance is observed at 99% confidence level.

4.5 Simultaneous Optimization

The technique of simultaneous optimization of several variables proposed by Derringer and Suich[16] for applications in rubber processing industry is extended for optimizing machining response variables such as dimensional instability, residual stress, surface finish, tool life and material removal rate and derived corresponding independent variables such as υ, f, d, α and r for experimental validation and ready applications. In simultaneous optimization the predicted σ_c, σ_I, T, R_a, MRR and $DIMI$ are transformed into respective desirability functions. The individual desirability's are then combined using the geometric mean to assess the desirability of the combined response. Single sided transformations of the form (9) for σ_c, σ_I, T, R_a, MRR and double sided transformation of the form (10) for $DIMI$ are used for obtaining the corresponding desirability functions.

$$d_i = \begin{cases} \left[\dfrac{y - y_{max}}{y_{min} - y_{max}}\right], & y_{min} < y < y_{max} \\ 0 & y \geq y_{max} \\ 1 & y \leq y_{min} \end{cases} \quad (9)$$

$$d_i = \begin{cases} \left[\dfrac{y - y_{min}}{y_c - y_{min}}\right], & y_{min} \leq y \leq y_c \\ \left[\dfrac{y - y_{max}}{y_c - y_{max}}\right], & y_c \leq y \leq y_{max} \\ 0 & y < y_{min},\ y > y_{max} \end{cases} \quad (10)$$

4.6 Optimization criterion

Generally, the tolerance band of modern jet engine components is classified into four groups

Group I - 5 - 10 microns range
Group II- 10 - 20 microns range
Group III- 20 - 30 microns range
Group IV- 30 - 40 microns range

There are only very few components which calls for the tolerance group of 5-10 microns which are achieved either by jig boring or girding operations. Since the present study is limited to turning operation, only Group II to Group IV tolerance range are considered as criterion for optimization. Simultaneous optimization is done for these three groups. These tolerance groups decide the maximum and minimum acceptable constraints on the dimensional instability. The mid point of this range is taken as the central value for the dimensional instability where its desirability becomes unity. The maximum and minimum acceptable constraints on residual stress, tool life and surface finish are selected based on the practical experience and is given in Table 3. Minimum and maximum constraints on *MRR* are based on the minimum values of υ, f, d and limiting power of the lathe. Within the given tolerance group, individual desirability's are computed for different combinations of input machining parameters υ, f, d, α and r by varying them in discrete steps. Finally maximum composite desirability is evaluated by numerical comparison. A computer program is written in C-language to print the optimum values of σ_c, σ_l, T, R_a, *MRR* and *DIMI* as soon as the maximum composite desirability is reached. The optimum parameters are listed in Table 4.

4.7 Experimental validation of Optimum Parameters

To validate these derived optimum machinability parameters for the actual applications on critical components for the acceptable tolerance range of 10 to 20 microns, tests were conducted on ring type specimen by following the same procedure that followed for generating initial experimental data. Five recorded response variables were compared with predicted. The inspection data are listed in Table 5. The inspection report clearly shows that the dimensional changes are well within the predicted limit. Repeated tests were conducted with same parameters and measured values scatter within 5%. This experiment validates that predicted optimum machinability parameters are most reliable. Similar validations have been done for other tolerance groups.

4.8 Validation of optimum parameters on actual components of jet engine

The predicted optimum parameters for the tolerance range of 10 to 20 microns were validated for practical application on compressor disc. By using these optimized υ, f, d, α and r the 400(+0.02, 0.00)mm locating diameter was machined. Immediately after machining dimensions were checked, it was found to be 400(+0.010, 0.00) mm. After 360 hours same dimension was 400(+0.015, 0.00), which is within the acceptable tolerance band. Fig.14 and Fig.15 show the effect of non-optimized and optimized parameters on dimensional changes. The results adequately prove the validity of this optimization process and the parameters for the practical applications.

5 CONCLUSION

The following conclusions have emerged form the present study.

1. Investigations on plastic deformation characteristics of Inconel 718 concludes that shear localized chips of Inconel 718 very similar with titanium Ti-6Al-4V alloy. Deformation twinning is noticed in Inconel 718 and titanium alloy. Inconel 718 also behaves similar way of titanium alloy in dimensional instability and magnitude is much higher than titanium alloys where as similar phenomenon is not noticed in other nickel based alloys.
2. Effect of machinability parameters on plastic deformation and resulting residual stresses have been established. Negative rake angle increases and positive rake angle decreases the residual stresses.
3. As the chip tool contact length increases cutting force and frictional forces increases, therefore the controlled chip-tool contact length reduces residual stresses compared to natural chip tool contact length.

Table 3 Constraints on response variables

Response variables	Maximum constraint	Minimum constraint
σ_r	200	0
σ_l	20	0
T	20	5
R_a	0.8	0.2

Table 4 Optimized parameters

Acceptable dimensional Instability in microns	Independent parameters			Dependent or Response parameters			Composite Desirability
	υ / α	f / r	d	σ_r / *MRR*	σ_l / *DIMI*	T / R_a	
Range II 10 to 20 microns	14 / 6	0.04 / 0.4	0.4	62.6 / 196	8.54 / 15.6	10.2 / 0.516	0.296436
Range III 20 to 30 microns	20 / 6	0.04 / 0.4	0.5	99.9 / 360	10.9 / 24.9	8.4 / 0.463	0.311526
Range IV 30 to 50 microns	26 / 6	0.04 / 0.4	0.8	152.4 / 780	14.8 / 38.1	7.2 / 0.486	0.261750

Table 5 Dimensional instability measurements

Sl. No.	Specimen ID/OD location	Measurement immediately after machining in mm		Measurement after 360 hours in mm		Actual change in dimension in mm	
		Mean diameter	Roundness	Mean diameter	Roundness	Mean diameter	Roundness
1	ID at 5 mm	60.5569	0.0145	60.5569	0.0137	no hange	0.008
2	ID at 15 mm	60.5634	0.02157	60.5630	0.0186	0.001	0.0029
3	OD at 5 mm	66.3993	0.0151	66.3982	0.0136	0.0011	0.0015
4	OD at 15 mm	66.3948	0.0125	66.3939	0.0118	0.009	0.007
5	OD at 25 mm	66.3931	0.0117	66.3924	0.0094	0.007	0.0023

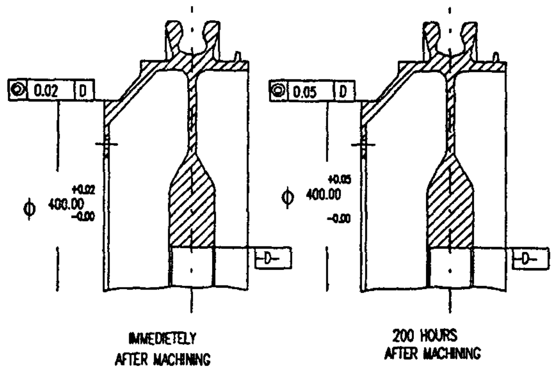

Fig.14 Effect of non-optimized parameters on dimensional instability

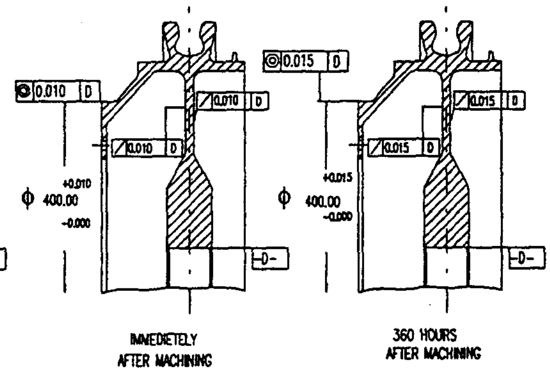

Fig.15 Effect of optimized parameters on dimensional instability

4. The empirical relationships for prediction of surface residual stresses, dimensional instability, surface finish, and tool life in machining of Inconel 718 superalloy has been established.
5. The cutting speed, feed, depth of cut, rake angle, nose radius significantly influences the residual stresses, dimensional instability, surface finish and tool life.
6. Optimum of machinability parameters(v, f, d, α and r) has been established by simultaneous optimization of six response variables(σ_c, σ_t, T, R_a, MRR and $DIMI$) with surface response methodology and desirability functions. The optimized results are verified with experimental results and it is found to be adequate.
7. Optimized machinability parameters for turning operations to control the dimensional instability on critical aerogas turbine engine components within the tolerance range of 10 to 20, 10 to 30, 30 to 50 microns are established for shop floor applications.

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