# Chapter 42
# Effect of Machining Parameters on Surface Integrity in End Milling of Inconel 625

**Ramesh Rajguru and Hari Vasudevan**

**Abstract** This study exclusively deals with surface integrity aspects, such as residual stresses, surface roughness, and micro-hardness, in the end milling of Inconel 625 using TiAlSiN-coated carbide-cutting tools distinctively developed for dry machining of the nickel-based superalloy. The aim of this research was to build up a set of guiding principles, which would help out the selection of the proper cutting conditions and tool geometry to enhance surface integrity of nickel-based superalloy Inconel 625. As part of the study, the effect of cutting speed, feed per tooth, radial depth of cut and radial rake angle on surface roughness, residual stresses and microhardness was studied. It was observed from results of analysis of variance that the surface roughness is significantly influenced by feed per tooth, followed by cutting speed, while radial depths of cut and radial rake angle have a small influence. The experimental results revealed that the minimum surface roughness (0.084 µm), residual stress (123.2 Mpa) and maximum micro-hardness (344) were observed at higher cutting speed (90 m/min), positive radial rake angle (13°), lower feed per tooth (0.05 mm/tooth), and lower radial depth of cut (0.2 mm). Based on the experimental analysis, it was observed that the higher cutting speed, the lowest feed per tooth, and lower radial depth of cut coupled with the use of positive radial rake angle can ensure induction of superior surface integrity in the machined surfaces.

**Keywords** Inconel 625 · Difficult to cut material · End milling · Surface integrity · Residual stresses and micro-hardness

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## 42.1 Introduction

Ni-based super alloy is an uncommon class of metallic materials with an exceptional combination of greater thermal strength, toughness, and resistance to deterioration in a corrosive or acidic environment. With the progress in the technology of aero-engines, many difficult to machine materials, such as Inconel 625 nickel-based superalloy, are being used extensively in the manufacturing of new engines, besides its enormous uses in marine, chemical and oil and petrochemical industries [1]. Surface integrity is determined by surface roughness, texture, micro-hardness and residual stresses [2]. Residual stresses can be defined as the stresses that remain within a material or body after manufacture and material processing in the absence of external forces or thermal gradients [3]. For the first time, it was Henriksen who explored RS developed in a machining [4].

In the machining process, the residual stresses are created from inhomogeneous material deformation, because of mechanical loading, thermal gradient and phase transformation by the action of cutting tool. Further residual stresses are created nearby the crystal defect in the material as well as at the grain boundary [5, 6]. Surface roughness is used as primary indicated method of quality of surface finish. It is used to test the quality and quantity of the surface integrity [7]. Micro-hardness is one of the significant parameters of surface integrity and its measurements are vital in the determination of degree of work hardening, corrosion resistance and wear resistance and to recognize metallurgical changes in the surface and subsurface after machining [8–12]. Machinability of any material is greatly enhanced by selection of cutting tool material and tool geometry such as nose radius, rake angle, and clearance angles; because, the geometry of the cutting tool shows a huge part in governing heat [13, 14]. A positive rake angle is recommended as it minimizes work hardening of the machined surface by shearing the chip away from the workpiece [15].

The execution of dry machining is not without troubles such as reduced tool life. However, an advance of tool technology the demands of dry machining becomes less challenging and the possibility for user savings gets better [16].

In a review on the machinability of nickel-based alloys by E. O. Ezugwu, problems related to the machining process of superalloys, tool wear, and the mechanisms of tool failure were recognized and discussed. Further, cutting tool geometry also influenced on machinability of nickel-based alloys [17]. In another review work on machinability characteristics of nickel-based superalloy by Kaya and Akyuz [18], increase of cutting speed and feed rate is unfavorable to machining induced residual stress magnitudes. Moreover, cutting speed is found to be remained as the key factor contributing to tool wear in machining of nickel-based superalloys. Further, there were inverse relations between cutting speed and cutting forces. Pawade et al. [19] investigated on the influence of cutting parameters and cutting tool geometry, namely cutting speed, feed rate, depth of cut and edge geometry on residual stress, micro-hardness and degree of work hardening, during high-speed turning operation on Inconel 718 Ni-based superalloy with PCBN rhomboidal shaped inserts. The results revealed that the higher cutting speed, the lowest feed rate, and moderately depth of cut coupled with the use of edge geometry could ensure induction of superior surface integrity in the machined surfaces.

Bhopale et al. [20] conducted an experimental investigation to evaluate the effect of ball-end milling parameters on surface integrity aspects of Inconel 718. Their study pointed out that surface roughness is a function of chip cross-sectional area. Further, micro-hardness is significantly affected by the cutting speed and cutting path at 60 μm depths. Moufki et al. [21] developed an analytical model by including the influence of moderate cutting speed, feed per tooth, axial depth of cut, and radial depth of cut with solid PVD, TiSiN-coated carbide cutting tool during milling operation. The predicted cutting forces are in good harmony with testing data for dry end milling of Inconel 718. In a review of micro-hardness measurement by Singaravel and Selvaraj [22], it is reported that the micro-hardness of the machined components mainly influenced by process parameters, cutting environment conditions (dry or wet), and types of coated tool as well as tool geometry.

El-Wardany et al. [23] investigated the effect of cutting conditions and tool wear on micro-hardness and residual stresses of die material in high-speed hard machining in dry turning using polycrystalline cubic boron nitride (PCBN) tool. Their results showed that the maximum increase in the micro-hardness underneath the surface occurs at a feed of 0.05 mm/rev and depth of cut of 0.4 mm. Moreover, changes in micro-hardness do not occur further than the depth of 55 μm. Ezugwu and Pash by conducted high-speed milling on Inconel 718 with different cutter/insert combinations. The result revealed that positive cutter/insert grouping results in a smooth cutting action, lesser power consumption, and a better surface finish [24].

Although considerable work on machining of nickel-based alloy Inconel 718 has been investigated and reported in literature, similar work on different other grades of the alloy is relatively scarce. It is known that the machining characteristics of a particular workpiece material depend primarily on its composition, microstructure, and thermo-mechanical properties. Therefore, it is also important to evaluate the machinability of Inconel 625 with sizable difference in chemical and other properties from other grades, as so far the same is unknown. Furthermore, as milling is a widely used material cutting operation, besides turning and drilling, especially in aerospace for machining of engine parts, engine compressor disks, bearing ring and marine and power generation industries, this study is expected to contribute further in enhancing the understanding related to many allied industrial applications. It could also give useful inputs as applicable to many machining applications in the area of difficult-to-cut materials, carried out especially in small and medium enterprises (SME) manufacturing firms. In this context, we have performed the end milling operation on nickel-based superalloy Inconel 625 to investigate the effect of cutting conditions on surface integrity aspects.

## 42.2 Experimental Details

The work material selected for the study was nickel-based superalloy Inconel 625. The work specimens are flat plate 150 mm long, 50 mm wide, and 6 mm thickness, and all work specimens were heat created before the end milling operation. A four teeth guhring, Germany end mill of 12 mm diameter with variable helix angle, was used. The end mill cutter was a PVD TiAlSiN ultrahard coating specially designed for difficult-to-cut material, as shown in Fig. 42.1. Other properties of solid end mill cutter are illustrated in Table 42.1.

Cutting speed, feed per tooth, radial depth of cut, and radial rake angle were the four cutting conditions considered for dry end milling operations. The range of cutting conditions was selected based on available literature. Down-milling operations were performed using MAXMILL PLUS+ CNC vertical machining center with a cutting speed value of 50 and 90 m/min, feed per tooth value of 0.05 and 0.17 mm, radial depth of cut value of 0.2 and 1 mm and radial rake angle of 5 and 13°.

The end milling experimental setup used is represented by means of a labeled depiction as shown in Fig. 42.2.

Workpiece was mounted on a Kistler dynamometer associated with a charge amplifier to measure the cutting forces during the process. The experiments were conducted as various cutting conditions as per the L8 orthogonal array [25]. After machining, CNC wire cut was used to cut work specimen of the size 50 mm × 6 mm × 5 mm, across the machine surface for measurement of the residual stress and micro-hardness. The measurement for surface roughness was done on Taylor Hobson Talysurf 4 setup as shown in Fig. 42.3 with data acquisition by a diamond tip stylus profiler using SeSurf.

Micro-hardness of the machined surface was measured using Vickers indenter at a load of 100-g force for 15 s, with square-based pyramid. Residual stress was measured using X-ray diffractometer: Philips make Panalytical X'Pert Pro residual stress measuring unit with software X'pert stress for residual stress testing.

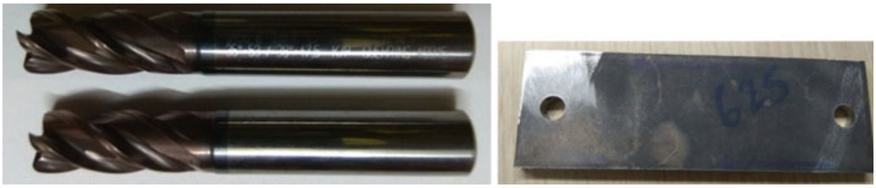


**Fig. 42.1** Solid carbide end mill and work material Inconel 625

**Table 42.1** Experimental conditions

| **Machine tool** | CNC milling machine |
|---|---|
| **Workpiece material** | Nickel-based superalloy Inconel 625, Size 150 × 50 × 6 $mm^3$ |
| Chemical composition (% by weight) | Ni 61.64, Cr 21.10, Fe 3.52, Nb 3.70, Mo 9.05, Al 0.17, Ti 0.23, Co 0.08, Mn 0.14,Si 0.16, C 0.05 |
| **Material properties** | |
| Density (kg $m^{-3}$) | 8.4 |
| Tensile strength (MPa) | 1050 |
| Elastic modulus (GPa) | 205 |
| Hardness (HB) | 320 |
| Poisson’s ratio | 0.31 |
| **Cutting tools** | Solid coated carbide end mill cutters (Guhring, Germany) |
| Cutter diameter ($d$) | 12 mm |
| No. of flutes ($Z$) | 4 |
| Helix angle (variable) | 35°.53, 38.47° |
| Nose radius ($r$) | 1.5 mm |
| **Process parameters** | |
| Cutting speed ($V_c$) | 50, 90 m/min |
| Feed per tooth ($f_z$) | 0.05, 0.17 mm/tooth |
| Radial depth of cut ($a_e$) | 0.2, 1.0 mm |
| Radial rake angle ($\alpha$) | 5°, 13° |
| **Cutter path** | Down milling |
| **Environment** | Dry |

## 42.3 Result and Analysis

### *42.3.1 Analysis of Surface Roughness Using ANOVA*

The analysis was performed to measure the effects of the cutting speed, feed per tooth, radial depth of cut, and radial rake angle on the response surface roughness. This analysis was carried out for a level of confidence of 95%. From the ANOVA result, it was established that the feed per tooth, cutting speed, and radial depth of cut have a significant influence on surface finish while radial rake angle have no effect at 95% confidence level. It was obtained that the feed per tooth is relatively significant factor than other parameters. The percent contributions of parameters found that the effect of feed per tooth in affecting surface roughness is significantly greater than the cutting speed, radial depth of cut, and radial rake angle.

The percent contribution of feed per tooth (64.14%), cutting speed (17.15%), and depth of cut (10.38%) in affecting the deviation of surface roughness are significantly

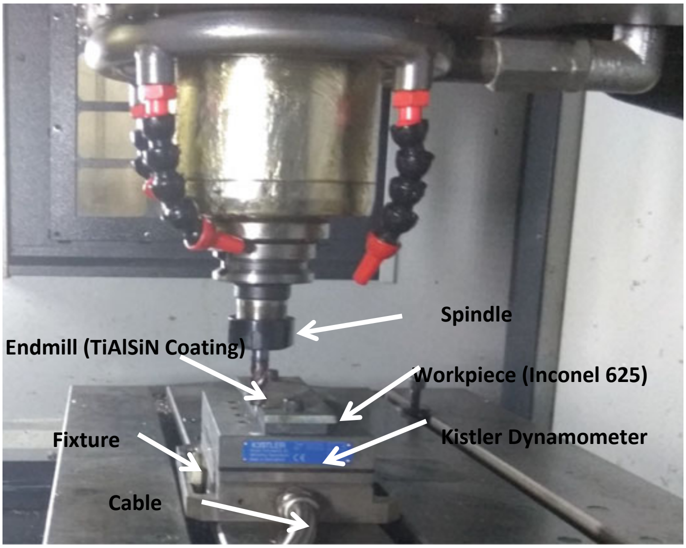


**Fig. 42.2** Experimental setup

**Fig. 42.3** Taylor Hobson Talysurf setup and profile of surface roughness

larger (95% confidence level) as compared to the contribution of the other parameter as shown in Table 42.2.

It was observed from the main effects plot that surface roughness decreases as cutting speed increases from 50 to 90 m/min. Surface roughness increases drastically as feed per tooth increases from 0.05 to 0.17 mm/min and the effect of radial depth of cut is moderate on surface finish as shown in Fig. 42.4.

**Table 42.2** ANOVA for surface roughness

| Source | DF | Seq SS | Adj SS | Adj MS | *F* | *P* |
|---|---|---|---|---|---|---|
| Cutting speed | 1 | 0.6039 | 0.6039 | 0.6039 | 6.32 | 0.087 |
| Feed per tooth | 1 | 2.2578 | 2.2578 | 2.2578 | 23.62 | 0.017 |
| Radial depth od cut | 1 | 0.3655 | 0.3655 | 0.3655 | 3.82 | 0.145 |
| Radial rake angle | 1 | 0.0057 | 0.0057 | 0.0057 | 0.06 | 0.822 |
| Error | 3 | 0.2867 | 0.2867 | 0.0955 | | |
| Total | 7 | 3.51970 | | | | |

$S = 0.309163$, $R$-Sq = 91.85%, $R$-Sq (adj) = 80.99%

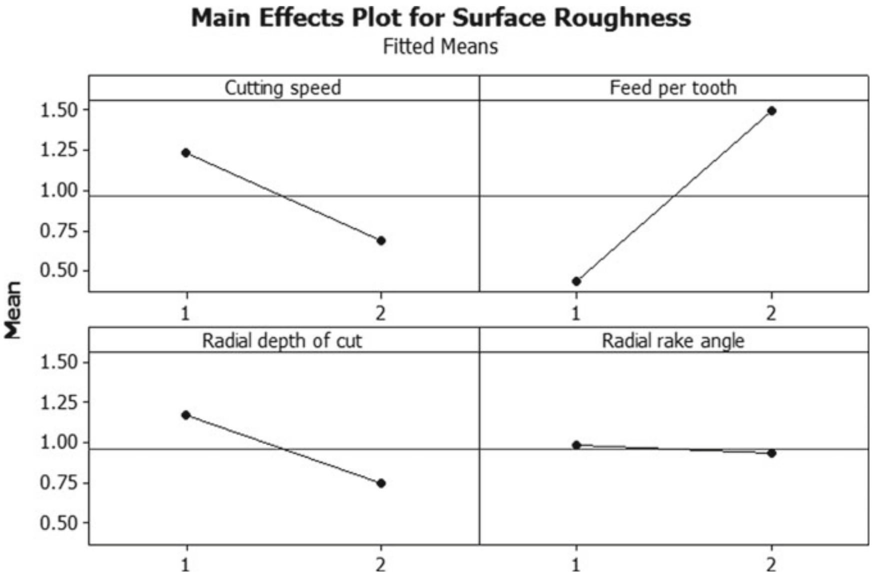
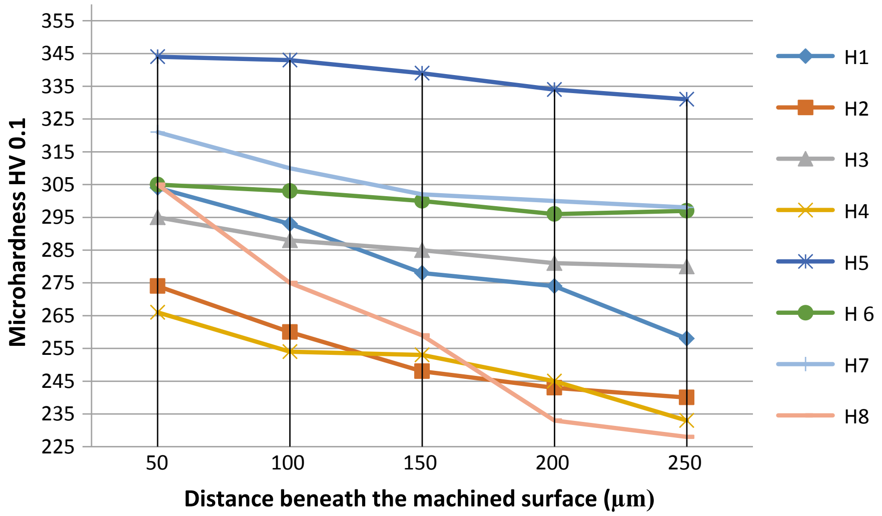


**Fig. 42.4** Main effects plot for surface roughness

## 42.3.2 Analysis of Micro-hardness

Micro-hardness of machined surface is higher near the machined surface layer and decreases with the depth (50, 100, 150, 250 μm as shown in Fig. 42.5) of machined subsurface due to the reduction in the work hardening of the Inconel 625, underneath the surface layer (similar result reported by Nandkumar N. Bhopale for Inconel 718). Maximum hardness is obtained at higher cutting speed (90 m/min), lower feed per tooth (0.05 m/min), lower radial depth of cut (0.2 mm), and higher radial rake angle (13°).



H1 $V_c$= 50 m/min, $f_z$ = 0.05 mm/tooth, $a_e$= 0.2 mm, α =5

H2 $V_c$= 50 m/min, $f_z$ = 0.05 mm/tooth, $a_e$= 1 mm, α =13

H3 $V_c$= 50 m/min, $f_z$ = 0.17 mm/tooth, $a_e$= 0.2 mm, α =13

H4 $V_c$= 50 m/min, $f_z$ = 0.17 mm/tooth, $a_e$= 1 mm, α =5

**H5 $V_c$= 90 m/min, $f_z$ = 0.05 mm/tooth, $a_e$= 0.2 mm, α =13**

H6 $V_c$= 90 m/min, $f_z$ = 0.05 mm/tooth, $a_e$= 1 mm, α =5

H7 $V_c$= 90 m/min, $f_z$ = 0.17mm/tooth, $a_e$= 0.2 mm, α =5

H8 $V_c$= 90 m/min, $f_z$ = 0.05 mm/tooth, $a_e$= 1 mm, α =13

**Fig. 42.5** Effect of micro-hardness on machined subsurface under different cutting conditions

### *42.3.3 Analysis of Residual Stresses*

Residual stress measurement was done using Panalytical (X pert pro model, Philips) at IIT Bombay. Before the workpiece was mounted on X-ray diffractometer, they were electropolished at −40°. To compute the residual stresses, the Sin2ϕ technique, which is based on Bragg's law, was used. The *d*-spacing was measured by tilting the workpiece at the different "ϕ" angles (Ref. Fig. 42.6).

It was found that the residual stresses on the machined surface are tensile for the whole range of cutting conditions and the minimum tensile stress was 123.2 Mpa. The reason can be that the thermal effect dominates than mechanical loading, leading to tensile residual stresses as well as the thermal effect of the CNC wire cut. It could be possible to convert the tensile residual stresses to compressive by appropriate selection of cutting conditions along with water jet cutting of workpieces after machining across the machine surface for measurement of the residual stress.

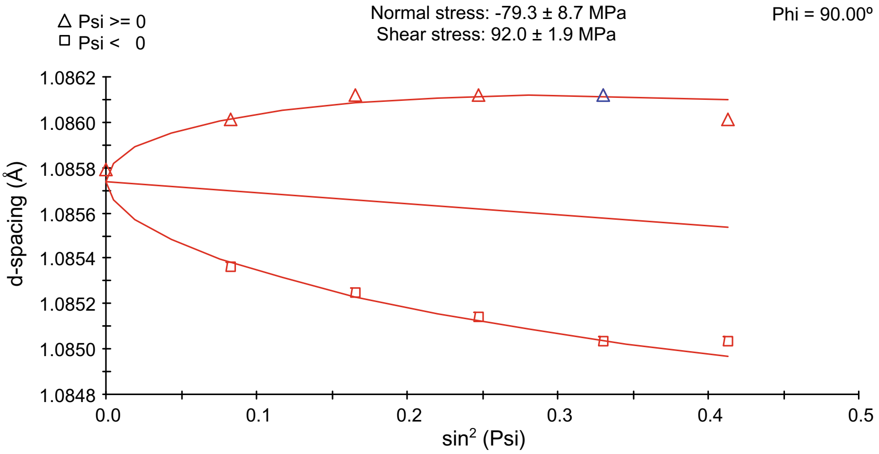


**Fig. 42.6** Measurement of *d*-spacing at different ‘ϕ” angles

## 42.4 Conclusion

In this study, an experimental investigation into the end milling of nickel-based superalloy Inconel 625 was conducted in order to analyze the influence of the machining parameters on surface integrity characteristics, such as surface roughness, microhardness, and residual stresses.

The surface roughness was analyzed using ANOVA and main effect plot. It was observed from results of analysis of variance that the surface roughness is significantly influenced by feed per tooth, followed by cutting speed. While radial depth of cut and radial rake angle have a smaller influence.

The percent contribution of feed per tooth (64.14%), cutting speed (17.15%), and depth of cut (10.38%) in affecting the deviation of surface finish were significantly larger (95% confidence level) as compared to the contribution of the other parameters.

It was observed from the main effects plot that the surface roughness increases drastically as feed per tooth increases from 0.05 to 0.17 mm/min.

The experimental results revealed that the minimum surface roughness (0.084 μm), residual stress (123.2 Mpa) and maximum micro-hardness (344) are observed at higher cutting speed (90 m/min), positive radial rake angle (13°), lower feed per tooth (0.05 mm/tooth), and lower radial depth of cut (0.2 mm).

Based on the experiment analyzed, it was observed that the higher cutting speed, the lowest feed per tooth, and lower radial depth of cut coupled with the use of positive radial rake angle could ensure induction of superior surface integrity in the machined surfaces.

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## References

1. Hanasaki, S., Fajiwara, J., Touse, M.: Tool wear of coated tools when machining and high nickel alloy. Annu. CIRP **39**(1), 77–80 (1990)
2. Davim, J.P.: Surface Integrity in Machining. Springer-Verlag, London (2010)
3. Ren, X.D., Zhan, Q.B., Yang, H.M., Dai, F.Z., Cui, C.Y., Sun, G.F., Ruan, L.: The effects of residual stress on fatigue behavior and crack propagation from laser shock processing-worked hole. Mater. Des. **44**, 149–154 (2013)
4. Henriksen, E.K.: Residual stresses in machined surfaces. Trans. ASME **73**, 69–74 (1951)
5. Ee, K.C., Dillon, O.W., Jawahir, I.S.: Int. J. Mech. Sci. **47**(2005) 1611
6. Guo, Y.B., Li, W., Jawahir, I.S.: Surface integrity characterization and prediction in machining of hardened and difficult-to-machine alloys: a state-of-art research review and analysis. Mach. Sci. Technol. **13**, 437–470
7. Ulutan, D., Ozel, T.: Int. J. Mech. Tools Manuf. **51**(2011), 250
8. Kundrák, J., Mamalis, A.G., Gyani, K., Bana, V.: Surface layer microhardness changes with highspeed turning of hardened steels. Int. J. Adv. Manuf. **53**, 105–112 (2011)
9. Thakur, D.G., Ramamoorthy, B., Vijayaraghavan, L.: Effect of cutting parameters on the degree of work hardening and tool life during high-speed machining of Inconel 718. Int. J. Adv. Manuf. **59**, 483–489 (2012)
10. Krolczyk, G., Nieslony, P., Legutko, S.: Microhardness and Surface Integrity in turning process of duplex stainless steel (DSS) for different cutting conditions. J. Mater. Eng. Perform. **23**, 859–866 (2014)
11. Jiang, W., More, A.S, Brown, W.D., Malshe, A.P.: A cBN-TiN composite coating for carbide inserts: Coating characterization and its applications for finish hard turning. Surf. Coat. Tech. **201**(2006), 2443–2449
12. Dogra, M., Sharma, V.S., Sachdeva, A., Suri, N.M., Dureja, J.S.: Tool wear, chip formation and workpiece surface issues in CBN hard turning: a review. Int. J. Precis. Eng. Man. **11**, 341–358 (2010)
13. Groover, M.P.: Fundamentals of Modern Manufacturing: Materials, Processes, and Systems, 4th edn, pp. 585. Wiley, New York (2010)
14. Production Technology HMT, Ch. 3 Machinability Aspects in Machining, pp. 53–68. Tata McGraw Hill, Bangalore, India (1980)
15. Ezugwu, E.O.: Key improvements in the machining of difficult-to-cut aerospace superalloys. Int. J. Mach. Tools Manuf. **45**, 1353–1367 (2005)
16. Dry Machining's Double Benefit, Machinery and Production Engineering, pp. 14–20 (1994)
17. Ezugwu, E.O., Wang, Z.M., Machado, A.R.: The machinability of nickel-based alloys: a review. J. Mater. Process. Technol. **86**, 1–16 (1999)
18. Kaya, Eren, Akyuz, Birol: Effects of cutting parameters on machinability characteristics of Ni-based super alloys: a review, published by De Gruyter Open. Open Eng. **7**, 330–342 (2017)
19. Pawade, R.S., Joshi, S.S., Brahmankar, P.K.: Int. J. Mach. Tools Manuf. **48**, 15–28 (2008)
20. Bhopale, Nandkumar N., Joshi, Suhas S., Pawade, Raju S.: Experimental investigation into the effect of ball end milling parameters on surface integrity of Inconel 718. J. Mater. Eng. Perform. **24**, 986–998 (2015)
21. Moufki, A., Le Coz, G., Dudzinski, D.: End milling of Inconel 718 super alloy—an analytical modeling
22. Singaravel, B., Selvaraj, T.: A review of micro hardness measurement in turning operation, applied mechanics and materials. ISSN: 1662–7482, Vols. 813–814, pp. 274–278. https://doi.org/10.4028/www.scientific.net/AMM.813-814.274

23. El-Wardany, T.I., Kishawy, H.A., Elbestawi, M.A.: Surface integrity of die material in high speed hard machining, part 2: microhardness variations and residual stresses. J. Manuf. Sci. Eng. 122/633 (2000)
24. Ezugwu, E.O., Pashby, I.R.: High speed milling of nickel-based superalloys. J. Mater. Process. Technol. **33**, 429–437 (1992)
25. Phadke, M.S.: Quality Engineering Using Robust Design. Prentice Hall, Englewood Cliffs (1989)