Comparative evaluation of machining performance of inconel 625 under dry and cryogenic cutting conditions

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Abstract. Hast alloys, wasp alloys and tool steels are the most commonly used materials in nuclear engineering and aerospace industries. However, these materials are considered to be “Difficult to machine” which attracted several researchers to work in this domain with a view to obtain optimum machining performance. The present work explored the comparative evaluation of machining performance of Inconel 625 under dry and cryogenic cutting conditions from an industrial perspective with emphasis on cutting forces, tool-chip interface temperature, surface finish and tool life. Turning experiments which were planned using the orthogonal array of L27 were carried out using Tungsten carbide Al2O3 coated inserts varying the cutting speed, feed and depth of cut. Cutting forces generated during turning at varying cutting conditions were measured using three axis lathe tool dynamometer. It was found the combination of speed of 200 m/min, feed value of 0.04 mm/rev and depth of cut value of 0.2 mm gives the optimum cutting forces with superior surface finish and low tool chip interface temperature in dry cutting condition. Again for same combination of cutting parameters were tested with cryogenic coolant Liquid Nitrogen (LN2) and it was observed that cutting forces reduced up to 30%, surface roughness improved by 31.37% and temperature reduced by 71.67%.

Keywords: Cutting forces, Cutting temperature, Cryogenic coolant, Dry turning, Inconel 625, Surface finish.

1. Introduction

In today’s competitive market and with the advancement in the technology, it becomes very much imperative to manufacture better quality products at low cost and that too in minimum time. However, still today it’s a challenge to economically machine difficult-to-cut materials. Hast alloys, wasp alloys and tool steels are the most commonly used materials in nuclear engineering and aerospace industries. However, these materials are considered to be “Difficult to machine” which attracted several researchers to work in this domain with a view to obtain optimum machining performance. Enterprises can achieve maximum revenue by manufacturing excellent quality product at lower cost by optimizing cutting parameters. The quality of surface finish is commonly used as index of product quality and it is also critical in functional behavior of the components like machine tool parts, dies etc. The optimum performance from the turning process is possible only when all the control parameters like speed, feed, depth of cut and coolant which affect the process are selected properly and with prior investigation. This in turn demands the study and analysis of the process parameters and finding out the combination of optimal cutting parameters in order to improve the performance of turning process and to reduce the cost while achieving the required geometrical tolerance.
An area of research interest in turning is the analysis of cutting forces, as minimum power consumption is a never ending process. Among the three components of cutting force namely tangential force, radial force and feed force, tangential component of force prominently influences power consumption and can be obtained using the equation as given below:

\[ F_c = k_c \times \text{DOC} \times f \]

Where, DOC = Depth of cut in mm, \( f \) is feed in mm/rev and \( k_c \) is specific cutting energy coefficient in N/mm².

From the equation and studies reported on experimental investigations of cutting forces during machining [1-5], it has been understood that cutting force is mostly influenced by the depth of cut and feed and varies with specific cutting energy coefficient for different materials. Researchers carried out comparative evaluation of cutting forces using different cutting conditions and cooling medium with a view to obtain lower values of cutting forces and hence lowering power consumption requirement in machining. However, working in this machining domain is constantly going on with the advancement of new work materials and new cutting edge technology [6].

Another important parameter of research interest is obtaining minimum surface roughness during machining of “difficult to machine” materials as an optimum surface finish would influence performance of mechanical parts. Industries like aerospace and nuclear engineering find wide applications of difficult to machine materials to avoid distortion caused after heat treatment. About 50 wt% of aero-engine alloys are nickel-based alloys as they exhibit higher strength to weight ratio and ability to maintain high resistance to corrosion, mechanical and thermal fatigue, mechanical and thermal shock, creep, and erosion at elevated temperatures[7]. Inconel 625 is a super alloy “difficult to machine” material which offers excellent stability during heat treatment. Inconel 625 has gained popularity for applications where a high risk of distortion or cracking exists due to increased corrosion resistance, wear, & abrasion resistance. Machinability of Inconel 625 varies from low to medium and therefore it becomes necessary to study the effects of speed, feed, depth of cut and type of coolant with the emphasis on productivity, tool life improvement and reliable performance characteristics.

Machining industries are trying for high material removal rate with improved product quality. However, the major problem to achieve this is high cutting temperature and cutting forces during machining of Inconel 625. Conventional cutting fluid fails to provide proper cooling effect [8-9]. Moreover, use of oil based coolant is more prone to environmental pollution due to chemical breakdown of cutting fluid at high temperatures and can create operator health issue due to bacterial growth in cutting fluid [9]. On the other hand, requirement of pump, storage, chilling unit, filtration system, recycling etc. adds to cost and creates problem for disposal of cutting fluid which attracted many researchers to work in the domain of sustainable manufacturing. One such alternative, which is emerging as a significantly beneficial sustainable manufacturing process, is cryogenic machining. It is reported that using cryogenic fluid over dry machining provide less cutting forces, better surface finish and improved tool life. In cryogenic cooling, the work-piece or chip changes properties of material from ductile to brittle because, the ductile chip material can become brittle when the chip temperature is lowered so it improves discontinues chips formation [10].

Yakup and Muammer [11] described the various cooling approaches in cryogenic turning. First approach was to cool the cutting point through heat conduction by liquid nitrogen (LN2)flow at the tool chip-tool interface or delivery of liquid nitrogen at the chip-tool interface through the hollow cutting tool. Directing LN2at interface increased the machining performance and does not caused significant changes in properties of the work-piece and machine tool structure. Another approach in cryogenic cooling is to cool cutting zone, particularly tool-chip interface with liquid nitrogen by using nozzle. In cryogenic jet cooling method, LN2 is sprayed at tool rake and/or the tool flank. From the available literature, it is understood that due to localized cryogenic cooling reduces the tool face temperature which in turn reduced the possibility of chips welding to the tool resulting in better surface quality.

Hong and Din [9] elaborated different cooling approaches in cryogenic machining of Ti-6Al-4V. During their study they recorded the temperature in the cutting zone by using the K-type
thermocouple. Their study reported that by applying LN2 to close proximity of cutting tool, cutting temperature at the chip-tool interface can be reduced. Yusuf [12] evaluated the machining performance in cryogenic machining of Inconel 718. They observed lower values of cutting forces and better surface finish when using cryogenic cooling in comparison to dry machining. Bapat et al. [13] developed a numerical model to obtain temperature distribution.

Seong–chan Jan [14] study reported that friction coefficient between tool and work-piece depends on the cryogenic cooling approach, especially nozzle design and nozzle location. They observed lower values of friction coefficient when LN2 is delivered at the tool chip interference. Grzesik [15] conducted experiment on the influence of cryogenic cooling on process stability in turning operations and found that cryogenic machining presents a more sustainable alternative to conventional machining process via increased machining process stability and consequently increased productivity.

Dhar et al. [16] studied the influence of cryogenic cooling on tool wear, dimensional accuracy and surface finish during turning of AISI 1040 and 4340 steels. Their study concluded significant improvement in surface finish and reduction in cutting zone temperature at cryogenic cooling in comparison to dry cutting conditions. Jerold and Pradeep Kumar [17] cryogenic machining study concluded reduction in cutting temperature by 22%, cutting forces up to 38% under cryogenic cutting in comparison to dry machining. Although, a sufficient study is reported on use of cryogenic cooling during machining, very few have reported on comparative evaluation of machining performance of Inconel 625 under dry and cryogenic cutting conditions from an industrial perspective with emphasis on cutting forces, tool-chip interface temperature, surface finish and tool life. With this view, in the present study, machining performance of Inconel 625 was investigated under dry and cryogenic cutting conditions.

2. Experimentation

Experimentation work was carried out on specimen of diameter 40 mm and length 1000mm with the aim of improvement of the quality and reliability of the turning process. It was also intended to evaluate and understand the effect of the cutting forces and type of coolant on surface roughness during the turning operation.

2.1. Work-piece material

Inconel 625 was used as a work-piece material which is popularly used in applications like marine applications, aerospace industries, chemical processing plant, nuclear reactors, pollution control equipment, where properties like high surface finish, high corrosion resistance and wear resistance are of prime importance. Its hardness ranges between 45-50 HRC and the chemical composition is as follows: Nickel- 58%; Chromium- 20 to 23 %; Molybdenum- 8-10 %; Iron- 5%; Aluminium- 0.4 %; Titanium- 0.4 %; Carbon- 0.1 %; Manganese- 0.5 %; Silicon- 0.5 %; Cobalt- 0.5 %.

| Table 1. Physical and mechanical properties of Inconel 625 |
|-------------------------------------------------------------|
| Property                     | Value          |
| Density                     | 0.305 Kg/m³    |
| Melting Point range         | 2350-2460°C    |
| Thermal Conductivity        | 74 W/m°K       |
| Specific Heat               | 0.107 KJ/Kg°K  |
| Poisson’s ratio             | 0.312          |
| Tensile Strength            | 29.2 N/mm²     |
2.2. Experimental Setup and Tooling
Dry and cryogenic experiments were performed varying cutting speed, feed and depth of cut as shown in Table 1. Experiments were planned using the Taguchi L27 orthogonal array. Tungsten carbide inserts (Grade: TNMG 160408Al2O3 coated) were used and tool holder used was designated as WIDIA ID 4A MTJNR 2525M16.

**Table 2.** Experimental matrix for dry and cryogenic cutting.

| Parameter                  | Levels |
|----------------------------|--------|
| Speed (m/min)              | 50     |
|                            | 125    |
|                            | 200    |
| Feed (mm/rev)              | 0.04   |
|                            | 0.08   |
|                            | 0.12   |
| Depth of cut (DOC) (mm)    | 0.2    |
|                            | 0.3    |
|                            | 0.4    |

Kistler dynamometer 9257B was used to compute three components of cutting forces; feed force (Fx), thrust force (Fy), tangential force (Fz). It is piezo-electric dynamometer capable of 5 KN to 5 KN of direct measurement. Its high resolution enables the smallest dynamic changes in large forces to be measured. The instantaneous roughness criteria measurements (Ra) for each cutting condition were obtained by means of Mitutoyo roughness tester. Experiments were repeated four times and the result is the average of these values. Temperature at the cutting zone was recorded by using digital infrared thermometer temperature gun. The experimental set-up is shown in Figs. 1, 2 and 3.

**Figure 1.** Cutting tool mounted on dynamometer. **Figure 2.** Cryogenic spraying and machining set-up. **Figure 3.** Force measurement.
3. Result and Discussion
Dry and cryogenic experiments which were planned using the Taguchi L27 orthogonal array were performed using Al$_2$O$_3$ coated tungsten carbide inserts varying cutting speed, feed and depth of cut as shown in Table 1. Dry turning experiments were performed without use of coolant resulted in higher chip-tool interface temperature. However, higher heat generated at the tool-chip interface caused annealing and softening of the work material just ahead of the tool, made it easier to shear.

However, manufacturing industries try for high material removal rate (MRR) with higher quality of machined surface. On the other hand, using higher cutting parameters to achieve higher MRR generates large amount of heat and hence, higher cutting temperature which adversely affects tool life. Many a times lead to catastrophic failure of cutting tools which significantly affects machined surface quality. Cryogenic machining is emerging as a significantly beneficial alternative and sustainable manufacturing process. With this view, to have a comparative evaluation, experiments were also performed using cryogenic cooling at the same cutting parameters which were used for dry cutting experiments.

Experiments planned using the Taguchi orthogonal array provides systematic way of conducting experiments with consideration of all the levels of the parameter and factors taken into account. The Experiments were conducted using the Taguchi L27 design of experiments (DOE) method. The factors were selected based on literature review, pilot experiments and manufacturer recommendations for dry turning of Inconel 625 using Al$_2$O$_3$ coated tungsten carbide inserts. This study involves the study of process parameters like speed, feed and depth of cut and its effect on surface roughness value. The output parameters taken into consideration are cutting force ($F_x$), feed force ($F_y$), thrust force ($F_z$), surface finish ($R_a$) and temperature ($T$).

Experimental results obtained during dry turning of Inconel 625 using Al$_2$O$_3$ coated tungsten carbide inserts varying cutting speed, feed and depth of cut as shown in Table 3. Underlined and highlighted parameters shown in the Table 3 observed as optimum cutting parameters for lower value of surface roughness. However, parameters are to be optimized for lower values of cutting forces and minimum temperature along with the lower surface roughness. With a view to have comparative evaluation of machining performance under dry and cryogenic cutting conditions, experiments using cryogenic coolant (LN$_2$) were carried out at cutting parameters which produced lower value of surface roughness under dry cutting condition. Experiments were also carried varying the cutting speed at other two levels with constant values of feed and depth of cut which produced lower value of surface roughness under dry turning. Experimental matrix and responses obtained under cryogenic turning of Inconel 625 using Al$_2$O$_3$ coated tungsten carbide inserts is shown in Table 4. Each set of turning operation was repeated four times and the measured responses are averages of four experimental observations. It can be seen lower values of surface roughness, cutting forces and chip-tool interface temperature under cryogenic turning as against higher values observed under dry cutting.

### Table 3. Experimental results under dry turning.

| DOC | Feed | Speed | Ra (µm) | $F_x$ (N) | $F_y$ (N) | $F_z$ (N) | Temp ($^\circ$C) |
|-----|------|-------|---------|----------|----------|----------|-----------------|
| 0.2 | 0.04 | 50    | 0.701   | 57.0     | 63.0     | 77.0     | 35              |
| 0.2 | 0.04 | 125   | 0.663   | 48.4     | 43.8     | 72.2     | 40              |
| **0.2** | **0.04** | **200** | **0.612** | **69.5** | **70.0** | **60.1** | **60** |
| 0.2 | 0.08 | 50    | 1.001   | 69.3     | 41.9     | 88.2     | 57              |
| 0.2 | 0.08 | 125   | 0.981   | 96.6     | 62.9     | 125.7    | 70              |
| 0.2 | 0.08 | 200   | 0.838   | 75.1     | 93.1     | 153.3    | 91              |
Underlined and highlighted parameters shown in the Table 4 observed as optimum cutting parameters for lower value of surface roughness under cryogenic cutting and can be clearly seen lower values of responses as against dry turning. Comparative evaluation of machining performance under dry turning and under cryogenic turning obtained at optimum cutting condition of depth of cut of 0.2 mm, feed value of 0.04 mm/rev and at cutting speed of 200 m/min are shown in Table 5.

**Table 4.** Experimental results with cryogenic coolant at optimum parameters obtained under dry cutting.

| DOC | Feed | Speed | Ra(µm) | Fx (N) | Fy(N) | Fz (N) | Temp (°C) |
|-----|------|-------|--------|--------|-------|--------|-----------|
| 0.2 | 0.04 | 50    | 0.59   | 51.0   | 54.6  | 67.1   | 13        |
| 0.2 | 0.04 | 125   | 0.52   | 44.4   | 38.5  | 59.2   | 16        |
| 0.2 | 0.04 | 200   | 0.42   | 47.7   | 62.4  | 43.2   | 17        |

It can be seen that cutting forces, surface roughness and cutting temperature reduced when turning under cryogenic cooling as against dry turning. Cryogenic cooling reduces cutting forces by up to 31% as compared to dry turning operation. Surface roughness value observed to be 0.42 µm which was
improved by 31% when turning using cryogenic cooling. However, significant reduction around 72% in chip-tool interface temperature was observed which reduced a temperature from 60°C to a value of 17°C.

| Output Parameters       | Dry Cutting | Cryogenic turning | % Change. |
|------------------------|-------------|-------------------|-----------|
| Surface finish (µm)    | 0.612       | 0.42              | 31.37     |
| Feed force             | 68.30       | 47.70             | 30.16     |
| Thrust force           | 70.04       | 62.46             | 10.82     |
| Tangential force       | 60.01       | 43.20             | 28.01     |
| Temperature            | 60          | 17                | 71.67     |

Figure 4. Surface roughness comparison.

Figure 5. Temperature comparison.

4. Conclusion
Experiments were conducted using the Taguchi L27 design of experiments (DOE) method for dry turning of hard materials like Inconel 625 alloy using tungsten carbide inserts to find the combination of optimum input parameters like speed, feed and depth of cut. It was observed that depth of cut of 0.2 mm, feed value of 0.04 mm/rev and cutting speed of 200 m/min is the best combination to get lower surface roughness of 0.612 µm under dry turning and which further reduced to a value of 0.42 µm under cryogenic cooling condition. It was observed that using liquid nitrogen coolant can improve the performance of the turning process. By using liquid nitrogen coolant, cutting forces reduced up to 30%, surface finish improved by 31.37% which shows finishing operation can be replaced by turning operation with optimum parameters with cryogenic coolants. It was also observed that tool chip interface temperature reduced by 71.67% which helps to improve the tool life. In the present work, cutting parameters are optimized for lower value of surface roughness. However, parameters are required to be optimized for lower values of cutting forces and minimum temperature along with the lower surface roughness during turning of Inconel 625 alloy using tungsten carbide inserts under dry and cryogenic cooling cutting conditions.

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