Machinability of A Nickel Aluminide Intermetallic Alloy

S. Chatterjee

This article reports the results of an experimental study on the machinability of a nickel aluminide intermetallic alloy. Machining was conducted at various speeds, and results indicate low material removal rates. Chips collected for each test run were measured for thickness for shear angle calculation and were subsequently observed microscopically. Chip segmentation was observed microscopically, and a fluctuation in the shear angle was evidenced. A parameter characterizing the severity of the machining process, the chip reduction coefficient (K), was calculated from chip thickness measurements. The calculated values of K were found to be low, indicating a low severity of the metalcutting process. This, however, is in contract with the observed low rates of metal removal and low tool life. Thus, conventional metalcutting characterization parameters require re-examination in terms of machining high-strength materials.

Keywords
nickel aluminide, machining, metal cutting

1. Introduction

INTERMETALLIC alloys hold significant promise for the future in various commercial and noncommercial applications because of their unusual properties in a wide range of operating conditions. For instance, these materials exhibit high yield strength at high temperatures and high hardness and increasing wear resistance with temperature.[1] Nickel aluminide is one such class of intermetallics and is being considered as a potential material for steam and gas turbines, cutting tools, bearing, forging dies, automotive pistons, valves, aircraft fasteners, and heating elements for appliances. Various grades of this alloy possess the composition ranges shown in Table 1.[2]

Nickel aluminide (Ni_3Al) is an ordered intermetallic compound in which the aluminum atoms with nickel atoms as closest neighbors are ordered on face-centered cubic (fcc) sites of a unit cell.[3] In the polycrystalline form, Ni_3Al alloys possess low ductility and exhibit a tendency for brittle intergranular fracture.[4] Low cohesive strength at grain boundaries, embrittlement by impurities at grain boundaries, a low initial mobile dislocation density, and an inadequate number of independent slip systems that satisfy von Mises criteria for plasticity of polycrystalline material contribute to the limited ductility of Ni_3Al.[5] Microalloying of Ni_3Al with boron has improved the ductility, and the addition of zirconium has contributed to increased strength and established the potential of Ni_3Al as an engineering alloy.[2]

2. Background

The properties that deem nickel aluminide attractive as an engineering alloy also pose significant challenge to their fabrication. A variety of processes have been reported for alloy synthesis.[2,6] At present, however, there is a dearth of published data on machining aspects of Ni_3Al. Houghton *et al.*[7] conducted machinability tests using alumina-based ceramic and sialon inserts of different shapes at cutting speeds ranging from 121.92 to 609.6 m/min, feedrates ranging from 0.1016 to 0.254 mm/revolution, and depths of cut ranging from 0.635 to 1.5875 mm. They reported certain combinations of cutting conditions at which successful machining was possible. However, no statistical inference regarding the influence of cutting conditions on tool life was developed.

Elsayed and Scardina[8] report a tool life of 2 to 7 min in the machining of Ni_3Al alloys using ceramic inserts at cutting speeds ranging from 122 to 457 m/min, feedrates ranging from 0.1524 to 0.254 mm/revolution, and depths of cut of 1.58 and 1.27 mm, respectively. Chatterjee[9] and Chatterjee *et al.*[10] also observed an extremely low tool life in the dry and wet machining of Ni_3Al using ceramic inserts at speeds of 30.48 to 137.16 m/min, feedrates of 0.0762 to 0.2032 mm/revolution, and depths of cut of 0.127 to 0.381 mm, respectively.

Previous machining studies of Ni_3Al concentrated on determining the appropriate combination of speed, feed, and depth of cut for improved tool life. However, the mechanics of the chip formation process in the machining of Ni_3Al has not been addressed. It is therefore important to investigate the nature of chip formation for this material because such a study will reveal important machining characteristics.

The objective of this investigation was to determine (1) material removal rates at various machining conditions and (2) the mechanism of the chip formation process in oblique turning of Ni_3Al. Nonavailability of a tubular specimen constrained the cutting process to oblique conditions.

3. Theoretical Consideration

In this study, a cylindrical Ni_3Al sample was turned at various cutting conditions (see below). The machining process was characterized by the material removal rate, whereas the me-

Table 1 Nickel aluminide compositions

Nickel	81.98 to 88.08%
Chromium	7.8%
Boron	0.02%
Aluminum	8.5 to 11.5%
Zirconium	0.6 to 1.7%

S. Chatterjee, Department of Industrial Engineering, The University of Tennessee, Knoxville, Tennessee.

chanics of the process, characterized by the chip reduction coefficient, the shear angle, and metallurgical examination of the chip, are discussed below.

3.1. *Chip Reduction Coefficient*

The metalcutting process is characterized by deformation of work material in the primary and secondary shear zones under the action of the cutting tool. This deformation produces a chip that is thicker than the uncut chip thickness.[11] The chip reduction coefficient is an indicator of the severity of the cutting process; the higher this coefficient, the greater the deformation.[12] The chip reduction coefficient (K) for oblique cutting is given by:[12]

$$K = \frac{a_c\, b_c}{a_\gamma\, b_\lambda} = \frac{a_c\, b_c}{\dfrac{s \sin \varphi}{\cos \gamma_n}\ \dfrac{t}{\sin \varphi \cos \lambda_n}} = \frac{a_c\, b_c}{st}(\cos \gamma_n \cos \lambda_n) \quad [1]$$

where a_c is the thickness of the deformed chip; b_c is the width of the deformed chip; a_γ is the thickness of the undeformed chip at a rake angle γ_n in the normal plane; b_λ is the width of the undeformed chip at an inclination angle λ_n in the normal plane; t is the depth of cut; s is the feed rate; and φ is the approach angle.

Thus, knowing the tool geometry and cutting conditions, the value of K at a certain cutting speed can be determined by measuring the width and thickness of chips and determining the values of γ_n and λ_n. The rake angle for the cutting tools provided by the manufacturer are with respect to the tool (x-y system) axes. This requires a transformation of the rake angle for the inserts to the normal plane and the determination of λ_n.

3.2. *Transformation of Shear Angle and Tool Angles to Normal Plane*

The shear angle is an indicator of the severity of the metalcutting process, and for oblique conditions, it is usually measured in the normal plane. The shear angle in the normal plane of cutting is given by:[11]

$$\beta_n = \tan^{-1} \frac{\cos \gamma_n}{K - \sin \gamma_n}$$

This, it is necessary to transform the rake angle from the tool axis system to the normal plane system.

Now, it is known that:[11]

$$\tan \gamma_n = \tan \gamma_o \cos \lambda_n \quad [2]$$

$$\tan \gamma_o = \tan \gamma_y \cos \varphi + \tan \gamma_x \sin \varphi \quad [3]$$

$$\tan \lambda_n = \tan \gamma_y \sin \varphi - \tan \gamma_x \cos \varphi \quad [4]$$

Here, γ_y and γ_x are the rake angles with y and x directions, respectively, and are known from manufacturers specifications. The angle φ is specified by the cutting condition. For this study:

$\gamma_x = -5°$, $\gamma_y = -5°$, and $\varphi = 75°$

Therefore:

$\gamma_o = -6.11°$, $\gamma_n = -6.10°$, and $\lambda_n = -3.54°$

from the equations above. Thus, β_n can be found from the values of the chip reduction coefficient and can be determined from values of γ_n and λ_n.

3.3. *Metallurgical Analysis of Chips*

Metallurgical analysis of chips reveals the type of chip formed and the nature of the chip formation process. Continuous chips, discontinuous chips, and chips with built-up edges are formed depending on the work material and on the cutting conditions.[12] Segmented chips also have been observed to occur in the machining of hard-to-machine materials.[12] These segments are formed cyclically with movement of the plastic zone on the tool face for a short period of time followed by its retraction to a point ahead of the cutting tool.[12] Such types of chips are clearly visible in microscopic examination of chip mounts. It is customary to mount, polish, and etch chips collected from the machining process for microscopic analysis. In this study, some characteristics of the mechanism of chip formation were observed from such an analysis and will be discussed later.

4. Experimental Considerations

4.1. *Material*

The material for this investigation was nickel aluminide (IC 218) with the following composition: 82.9% nickel, 8.50% aluminum, 7.80% chromium, 0.80% zirconium, and 0.02% boron. The IC 218 solid, round bar was 381 mm long and 76.2 mm in diameter and possessed an extremely rough surface with visible pores and inclusions resulting from the casting process. These inclusions were 34.76 mm deep on average. Due to the poor surface finish, it was necessary to turn the exterior to produce a smooth surface. An 88.9-mm long portion of the stock was turned at 40 rpm, 0.254 mm depth of cut, at a feed rate of 0.7112 mm/revolution, and a lead angle of 15° with a carbide tool with negative rake angle to produce an acceptable experimental sample. Excessive tool wear and heat generation were noted at this stage.

4.2. *Equipment*

The lathe used for this investigation possessed a speed range of 40 to 2000 rpm and was equipped with a spray cooling system and automatic feed capabilities.

4.3. *Cutting Tool Material*

Ceramic (alumina reinforced with silicon carbide whiskers) inserts were used because of their high compressive strength and high hot hardness. These inserts were held in a tool folder fitted with chipbreakers. The inserts were triangular and the following tool angles were used:

Approach angle = 15°, $\gamma_x = -5°$, $\gamma_y = -5°$

4.4. *Cutting Conditions*

Dry cutting was performed to assess machinability, and the longitudinal feed rate was kept constant at 0.127 mm/revolution, whereas the depth of cut (DOC) varied from 0.127, 0.254, and 0.381 mm corresponding to finishing and roughing cuts, respectively. The test cutting speed range was between 121.92 and 304.8 m/minute. All machining parameters were in accordance with cutting tool manufacturers specifications.

4.5. *Metallurgical Examination of Chips*

Chips collected for each cutting condition were mounted, polished, and etched for microscopic analysis. The width and thickness of the chips were measured by a micrometer. The average of five measurements of width and thickness for each chip was used to compute K and the normal shear angle.

5. Results

5.1. *Material Removal*

The theoretical and the actual material removal rates (MRR) as a function of velocity are shown in Fig. 1, which shows that the material removal rate was very low. The actual material removal rate was less than the theoretical material removal rate for the most part and may have been due to the rapid burnishing of the cutting tool. In some cases, the theoretical material removal rate was less than the actual material removal rate. This could have been due to the expansion of the workpiece following cutting because of high heat generation with corresponding errors in diameter measurements. Similar results have been reported by Houghton *et al.*[7] and Elsayed and Scardina.[8] Based on available data and on results of this study, it is evident that Ni_3Al exhibits low machinability. It is thus necessary to investigate the effectiveness of other types of tool material, such as cubic boron nitride or other ceramics, in machining Ni_3Al. Nontraditional machining processes such as water jet cutting or laser beam machining may also be considered.

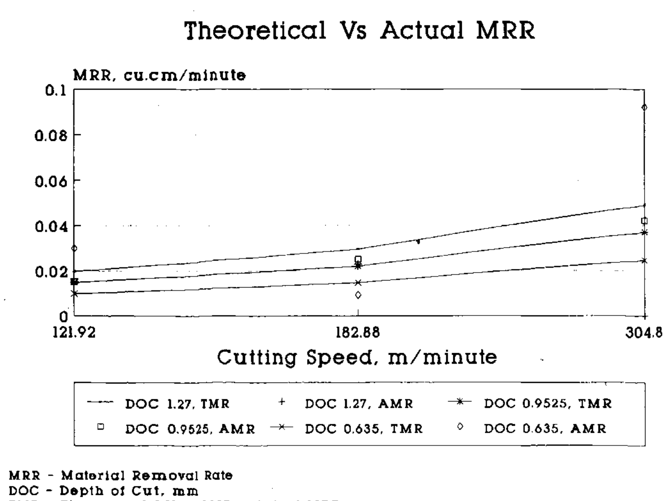

Fig. 1 Theoretical and actual material removal rates.

5.2. *Chip Reduction Coefficient Characteristics*

The dependence of K on the cutting velocity is shown in Fig. 2. The values of K range between 1.649 and 11.72. This range implies a variability in the forces developed during cutting. In metalcutting, typical values of K are found to range between 2 and 8 depending on cutting conditions. Low values of K are rather surprising considering the observed rapid wear of the cutting tools. Most inserts failed within two passes over the cutting length. Thus, in the machining of high-strength materials, such as Ni_3Al, the chip reduction coefficient may not be an appropriate indicator of the magnitude of the deformation undergone by the work material.

An interesting feature observed in Fig. 2 is the oscillation of the value of K for depth of cut of 0.254 mm at cutting speeds between 108.2 and 129.54 m/min. This implies an oscillation of the chip thickness resulting from a probable shifting of the

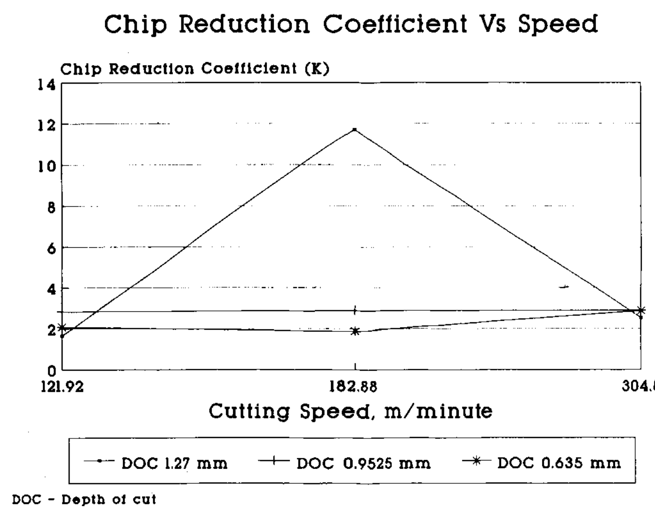

Fig. 2 Variation in chip reduction coefficient with cutting speed.

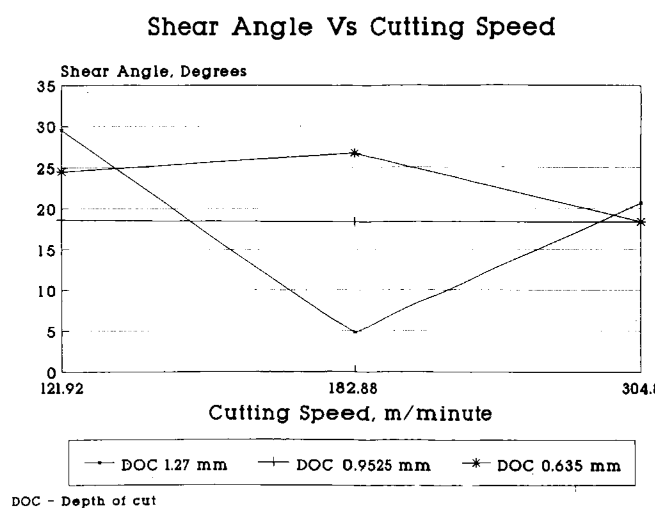

Fig. 3 Variation in shear angle with cutting speed.

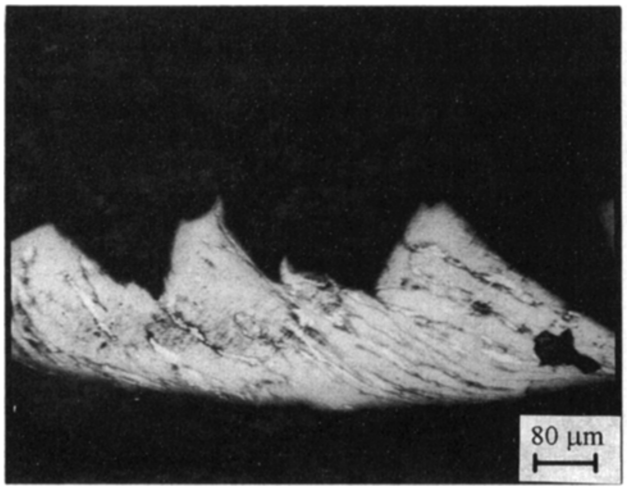

Fig. 4(a) Chip morphology of Ni_3Al. Cutting speed, 121.92 m/min; feed, 0.127 mm/revolution; depth of cut, 0.9525 mm.

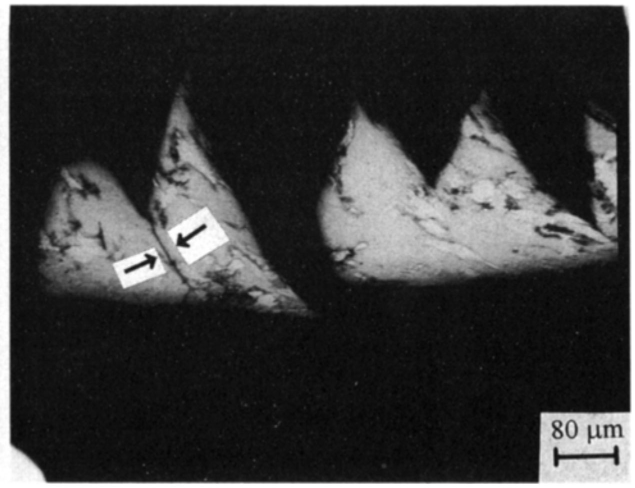

Fig. 4(b) Chip morphology of Ni_3Al. Cutting speed, 182.88 m/min; feed, 0.127 mm/revolution, depth of cut, 1.27 mm.

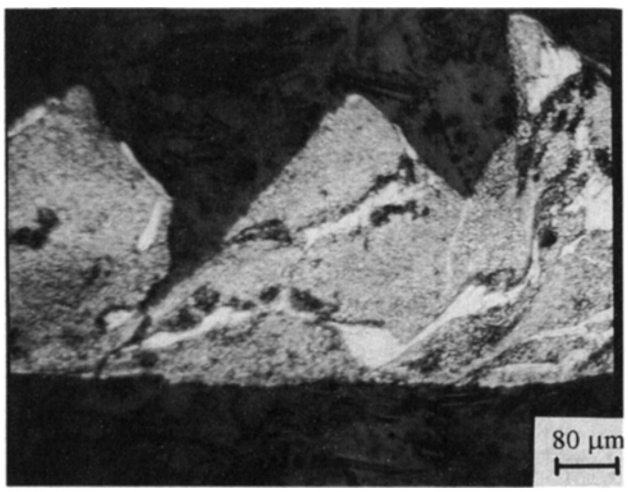

Fig. 4(c) Chip morphology of Ni_3Al. Cutting speed, 304.8 m/min; feed, 0.127 mm/revolution; depth of cut, 1.27 mm.

shear plane often observed in chip segmentation at different speeds.[14]

5.3. *Shear Angle Characteristics*

The dependence of the normal shear angle on the cutting speed is shown in Fig. 3. The calculated values of the normal shear angle ranges from 4.89 to 29.54°. A low shear angle implies the existence of a larger force during the cutting process, whereas a high shear angle indicates lower metalcutting forces.[11] No force measurements were made in this study; however, the rapid deterioration of cutting inserts seem to indicate the existence of high cutting forces and temperatures (the tip of the tools were observed to be glowing). Thus, the shear angle may not be a good indicator for the intensity of deformation and the forces involved in the machining of high-strength material such as Ni_3Al. Because the shear angle is related to K, an oscillation in the value of K is expected to bring about an oscillation in the value of the shear angle. This is evident for the machining of Ni_3Al at a depth of cut of 1.27 mm and may indicate a variation in chip thickness or shifting of the shear plane at different cutting speeds.[13]

5.4. *Metallurgical Analysis of Chips*

Chip formation modes were observed to be dependent on the cutting speeds. Chip segmentation was observed to be the dominant chip formation mode. Such segmentation characteristics are shown in Fig. 4 for the three cutting speeds and have also been observed to occur in the machining of titanium and steels.[13,14]Upsetting of the work material in the immediate vicinity of the cutting tool and oscillation and instability of the plastic zone are believed to be instrumental in the formation of segmented chips.[13,14]

An examination of Fig. 4(a), (b), and (c) show extensive grain deformation from the tool/workpiece interface area to the free surface. Also shown in Fig. 4(b) is the intensely sheared surface (arrows) where two segments are almost separated. This phenomenon can be contrasted with the chip segmentation characteristics shown in Fig. 4(a) where the intensely sheared surface is not evident. The chips examined in Fig. 4(a) were for a cutting speed of 121.92 m/min, whereas the corresponding cutting speeds for chips in Fig. 4(b) and (c) were 182.7 and 304.8 m/min, respectively. At higher speeds, the shear rate between segments might increase, and this may lead to the formation of the intense sheared surface shown in Fig. 4(b) and (c).

6. Conclusion

Based on the experimental investigation of machining Ni_3Al, the following conclusions can be made. Low material removal rates have been observed in the machining of Ni_3Al. Machining of Ni_3Al yields segmented chips. The chip reduction coefficient of the shear angle may not be a good indicator for predicting the ease or difficulty of machining Ni_3Al. Grain deformation is greater at the segment interfaces than within the segments.

Acknowledgment

The author acknowledges Oakridge National Laboratory for material support; Dr. M. Ramulu of the University of Washington, Seattle, for assistance in the development of the micrographs; and the assistance of Ms. K. Kolb in preparation of the manuscript.

References

1. K. Vedula, *Mater. Manufact. Proc.*, Vol 4 (No. 1), 1989, p 39-59
2. V.K. Sikka, *Mater. Manufact. Proc.*, Vol 4 (No. 1), 1989, p 1-24
3. T.S. Srivatsan and S. Sriram, Environmental Effects on Advanced Materials, The Metallurgical Society of AIME, 1990, p 15-21
4. C.T. Liu and J.O. Stiegler, *Science*, Vol 226, 1984, p 636-642
5. T.S. Srivatsan and S. Sriram, Low Density, High Temperature Powder Metallurgy Alloys, The Metallurgical Society of AIME, 1990, p 1-14
6. R.N. Wright, B.H. Rabin, and J.R. Knibloe, *Mater. Manufact. Proc.*, Vol 4 (No. 1), 1989, p 25-38
7. J.R. Houghton, R.M. Sundaran, and C.F. Yang, "Machinability Study on Nickel Aluminide Alloys," Final Report No. MCTR-05588-19 for Martin Marietta Energy Systems, 1988
8. M.A. Elsayed and J.T. Scardina, *J. Mech. Work. Technol.*, Vol 20, 1989, p 59-68
9. S. Chatterjee, "Machinability of Nickel Aluminide," Interim Report, Western New England College, Springfield, MA, 1989
10. S. Chatterjee, T.S. Srivatsan, P. Giusti, and S. Chandrashekhar, "Machinability and Tool Wear Characteristics of a Nickel Aluminide Intermetallic Compound," Working Paper, Western New England College, Springfield, MA, 1991
11. A. Bhattacharya, *Metal Cutting Theory and Practice*, Central Book Publishers, Calcutta, 1984, p 42-76
12. V. Arshinov and G. Alekseev, *Metal Cutting Theory and Cutting Tool Design*, Mir Publishers, Moscow, 1976, p 37-72
13. R. Komanduri and R.H. Brown, *J. Eng. Ind.*, Vol 103 (No. 1), 1981, p 33-51.14
14. R. Komanduri, T.A. Schroeder, D.K. Bandyopadhyaya, and J. Hazra, *Proc. Metall. Soc. AIME Fall Meeting*, Louisville, 1981, p 241-256