Chip Deformation Mechanism during Drilling of Nickel-based Superalloy FGH97

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Abstract. Nickel-based superalloy is widely used in aviation, aerospace, shipping and petrochemical industry. An experimental investigation was conducted to analyze the effects of cutting parameters on chip deformation during drilling process of nickel-based superalloy FGH97. Drilling experiments have been carried by means of a machining center YCM-V116B and TiN/TiAlN coated carbide drill bit SECO made SD203-8.0-27-8R1. The chip root is obtained by means of ourselves-made device. The chip deformation decreases with the increasing of cutting speed during drilling process of Ni-based superalloy. The larger the feed rate, the less the chip deformation is. When cutting speed is from 6 m/min to 12 m/min, the shear angle of drilling changes from 14.8 degrees to 19.9 degrees. When feed rate speed is from 0.03mm per tooth to 0.06mm per tooth, the shear angle of drilling changes from 13.7 degrees to 17.4 degrees.

1. Introduction
Nickel-based powder metallurgy superalloy materials are widely used in aviation, aerospace, shipping and petrochemical industries because of their excellent high temperature strength, thermal stability and thermal fatigue properties [1]. In the early 1960s, U.S. began to develop and apply Ni-based powder metallurgy superalloys firstly. U.S.S.R. began to study Ni-based powder metallurgy superalloys in the late 1960s. P.R. China began to develop Ni-based powder metallurgy superalloys until 1970s. Superalloy FGH95 is characterized as high strength at working temperature of 650 degrees Centigrade. Superalloy FGH96 can be used at temperatures up to 700-750 degrees Centigrade. It is a key material for preparing high performance engine turbine disk. Superalloy FGH97 prepared by plasma rotating electrode pulverizing and hot isostatic pressing has the advantages of high tensile strength and high creep resistance, and its crack propagation rate is one order of magnitude lower than that of FGH95 or FGH96 [2-4]. Ozcelik and Bageci [5] proposed a new method for measuring drilling temperature and measured the drilling temperatures of AISI-1040 and AI7050-T651. Sato, et al. [6] found that cutting thickness is the greatest factor affecting drill wear, drill wear of processing blind-hole is more serious than that of processing through -hole as drilling the same depth of hole because the drilling temperature near the bottom of blind-hole material increases sharply. The higher the drilling temperature, the faster the wear rate of drill is. Du [7, 8] investigated the microstructure of white layer appeared in the high speed machining of FGH95. Some research about cutting force [9-11], machined surface integrity [12, 13], bit wear and tool life [14, 15] during drilling process have been done.

The chip deformation in cutting process can reflect the essence of cutting phenomena. Nickel-based superalloy is of high strength, high hardness, low thermal conductivity and porous structure. It is more difficult to drill Ni-based superalloy than to turn or to mill because the heat generated in the drilling
process cannot be dispersed in time and the temperature in the drilling area is very high. The shear angle can characteristic the chip deformation degree in drilling process. It reflects the essence of physical phenomena such as drilling force, drilling temperature, bit wear and machined surface quality. It is very important to study chip deformation for optimizing the drilling parameters of Ni-based superalloy.

2. FGH97 Drilling Test

2.1. Properties of FGH97

Table 1 shows the composition of FGH97. The alloy elements dissolve a large number of solid solutions in Ni and Co resulting in the strengthening phase $\gamma'$. The content of strengthening phase $\gamma'$ in FGH97 is about 64% of the alloy mass fraction. Its tensile strength is 1510 MPa, yield strength is 1080 MPa and solid solution temperature is 1180-1190 degrees Centigrade. Therefore, the physical properties of FGH97 seriously restrict its machinability. Because of the special manufacturing process of materials, thermal-induced pores are formed in the material during the manufacturing process. When the tool cuts the induced pores, the tool will be impacted. The continuous impact has a great impact on the tool performance. Moreover, the existence of thermal-induced pores is not conducive to the heat dissipation during the cutting process. The thermal induced porosity also severely restricts the machinability of the material. So, FGH97 is very difficult to be machined.

| C  | Cr  | Co  | Al  | Ti  | W   | Nb  | Hf  | B   | Zr  | Mg  | Ce  | Ni  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.04 | 9.0 | 15.5 | 4.9 | 1.8 | 5.5 | 2.6 | 0.3 | $\leq0.015$ | $\leq0.015$ | $\leq0.02$ | $\leq0.01$ | bal |

2.2. Experiment and Test Setting

Drilling experiments have been carried by means of the machining center YCM-V116B as shown in Figure 1. TiN/TiAlN coated carbide drill bit SECO made SD203-8.0-27-8R1 is used to drill FGH97. The value setting of cutting speed, feed rate are shown in Table 2. Figure 2 shows the photograph of drilling experiment. The chip root is obtained by means of our self-made device as shown in Figure 2. The specimen is placed in the holder supported by two bearings and fixed by a positioning pin. When the positioning pin is pulled out, the specimen rotates with the drill bit to ensure that the chip and the specimen rotate with the drill bit together, so chip root can remain in the base material of specimen.

![Figure 1. Machining center YCM-V116B.](image-url)
Table 2. Cutting parameters.

| Factor                        | Level 1 | Level 2 | Level 3 | Level 4 |
|-------------------------------|---------|---------|---------|---------|
| Diameter of drill bit (mm)    | 8       | 8       | 8       | 8       |
| Cutting speed \( v_c \) (m/min)| 6       | 8       | 10      | 12      |
| Feed per teeth \( f_z \) (mm/z)| 0.03    | 0.04    | 0.05    | 0.06    |

Figure 2. Device for drilling chip root obtaining.

3. Test Results and Discussion

3.1. Test Results
Shear slip occurs in the first deformation zone, grain elongation, and the angle between the direction of cutting speed and the shear plane is the shear angle \( \phi \) as shown in Figure 3. The value of shear angle is opposite to the extent of chip deformation, that is, the less the shear angle, the greater the chip deformation is. The combinations of cutting speed, feed rate and the measured values of shear angle are shown in Table 3.

Table 3. Variables and test results.

| No. | Cutting speed \( v_c \) (m/min) | Feed per tooth \( f_z \) (mm/z) | Shear angle \( \phi \) (°) | No. | Cutting speed \( v_c \) (m/min) | Feed per tooth \( f_z \) (mm/z) | Shear angle \( \phi \) (°) |
|-----|--------------------------------|-------------------------------|-----------------|-----|--------------------------------|-------------------------------|-----------------|
| 1   | 6                              | 0.05                          | 14.8            | 5   | 10                             | 0.03                          | 13.7            |
| 2   | 8                              | 0.05                          | 15.9            | 6   | 10                             | 0.04                          | 13.9            |
| 3   | 10                             | 0.05                          | 16.1            | 7   | 10                             | 0.05                          | 16.1            |
| 4   | 12                             | 0.05                          | 19.8            | 8   | 10                             | 0.06                          | 17.4            |

3.2. Test Result Analysis and Discussion
As the diameter of drill bit is 8mm and feed rate is 0.05mm per tooth, the shear angles corresponding to cutting speed of 6m/min, 8m/min, 10m/min and 12m/min are shown in Figure 4. Figure 4 shows that the shear angle during drilling process of Ni-based superalloy increases, that is, chip deformation decreases with the increasing of cutting speed.

Figure 5 shows shear angles of drilling nickel-based superally FGH97 corresponding to feed rate of 0.03mm per tooth, 0.04mm per tooth, 0.05mm per tooth and 0.06mm per tooth as drill bit diameter is 8mm and cutting speed is 10mm/min. The shear angle of drilling nickel-based superally FGH97
increases with the increasing of feed rate. On the other word, drilling chip deformation of nickel-based superalloy will decrease with the increasing of feed rate.

Figure 3. Shear angle.  Figure 4. Effect of $v_c$ on shear angle.  Figure 5. Effect of $f_z$ on shear angle.

4. Conclusion
The chip roots in drilling nickel-base superalloy were obtained by using our self-made device, and the drilling deformation mechanism was studied. As the drilling speed increases, chip deformation decreases, and chip deformation becomes smaller with the increase of feed rate. When cutting speed is from 6 m/min to 12 m/min, the shear angle of drilling changes from 14.8 to 19.9 degrees. When feed rate speed is from 0.03mm per tooth to 0.06mm per tooth, the shear angle of drilling changes from 13.7 degrees to 17.4 degrees

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6. References
[1] Thellaputta G R, Chandra P S and Rao C S P 2017 Materials Today Proceedings 4 3712
[2] Zhang M, Li F, Yuan Z, Li J and Wang S 2013 Materials & Design 49 705
[3] Zhang M J, Li F G, Wang S Y and Liu C Y 2011 Materials Science and Eng.: A 528 4030
[4] Zhong B, Wang Y, Wei D, Zhang K and Wang J 2018 Int. J. of Fatigue 109 26
[5] Ozcelik B and Bagci E 2006 Materials & Design 27 920
[6] Sato M, Aoki T, Tanaka H and Takeda S 2013 Int. J Machine Tool & Manufacturing 68 40
[7] Du J, Zhang J and Wang L 2018 Rare Metal Materials and Engineering 47 2275
[8] Du J, Liu Z and Lv S 2014 Applied Surface Deicence 292 197
[9] Arif R, Fromentin G and Rossi F 2018 Procedia CIRP 77 425
[10] Uçak Nand Çiçek 2018 J.of Manufacturing Processes 31 622
[11] Hamade R F, Seif C Y and Ismail F 2006 Int. J Machine Tool & Manufacturing 46 387
[12] Wang X, Yang L and Qiao Y 2018 Procedia CIRP 77 370
[13] Venkatesan K 2017 J. of Advanced Research 8 407
[14] Wang X, Huang C and Zou B 2013 Int. J. of Advanced Manufacturing Technology 64 41
[15] Varote N and Joshi SS 2017 J. Materials Eng. and Perf. 26 4391