Effect of Milling Parameter on the Surface State of Ultra-high strength Steel 16Co14Ni10Cr2Mo

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Abstract: The machining mechanism and process parameters of ultra-high strength steel 16Co14Ni10Cr2Mo are still lack of complete understanding. By changing the milling condition, the influence of process parameters on cutting force, such as Radial milling depth, Axial milling depth, Feed per tooth and milling speed, is studied, and in the meanwhile that the surface morphology and hardness of 16Co14Ni10Cr2Mo after machining are analyzed. Indicating that the milling force increases with the increase of axial milling depth, feed rate and radial milling depth. With the increase of milling speed, the milling force reduces. The effect of axial cutting depth and radial cutting depth on cutting force is maximum. For 16Co14Ni10Cr2Mo ultra-high strength steel, it is suitable to use small cutting depth and high milling speed. On the surface of milling material, partial melting and partial oxidation of chips occur. When the milling speed and feed rate increased, the surface hardness of the material did not change significantly, and there was no work hardening.

1. Introduction
Ultra-high strength steel has the characteristics of high strength and high toughness, which is one of the preferred materials for the important load-bearing components of ships, aviation aircraft and military equipment [1,2]. However, from the viewpoint of manufacturability, the ultra-high strength steel generally has the characteristics of hard mass and poor thermal conductivity [3]. So it is difficult to perform cutting processing [4,5]. 16Co14Ni10Cr2Mo, a kind of ultra-high strength steel with low-carbon and highly alloyed characteristics, had the tensile strength at room temperature not less than 1620 MPa and the fracture toughness not less than 1430 MPa after the quenching and tempering treatment [6]. The ultra-high mechanical property always brought great difficulties to its mechanical machining process for achieving the necessary shape and size accuracy.

To solve the problem of hard machining of ultra-high strength steel, the key is to study the cutting mechanism [7,8]. Among them, cutting force is an important physical quantity in cutting process, which has an important influence on cutting heat, tool wear and machined surface quality [9,10]. Patel et al. [11] conducted an end milling study on AISI 304 stainless steel. The effects of spindle speed, feed speed and cutting depth on the cutting force and surface roughness were studied by the taguchi method. Kandrác Ladislav[12] carried out the two-dimensional cutting simulation of Ti-6Al-4V alloy, and analyzed the effects of different cutting speed, feed rate and tool geometric parameters on the
cutting force. In the process of high speed machining of Inconel 718, R.S. Pawade [13] analyzed the residual stress, microhardness and working hardening degree of the machined surface, and obtained the optimum machining conditions of the machined surface with high integrity. The effect of surface milling on microstructure and microhardness of Ti6Al4V material was studied by Moussaoui K [14], no plastic deformation layer or grain prolongation on the surface after milling; a slightly softened area was observed under the milling surface, but the microstructure did not change. The single factor test of high speed milling of titanium alloy TC17 with cemented carbide tools was carried out by Li Y [15], and the effect of cutting parameters on the surface microstructure of titanium alloy TC17 was studied. The results show that the milling speed, feed per tooth and milling depth have little effect on the surface microstructure.

The above studies shows that, cutting force is the main object of cutting parameters. Compared with the theoretical calculation, the experimental study can reflect the relationship between process parameters and cutting force more accurately and intuitively. Cutting is a thermodynamic coupling process, and the surface state of the material are affected by the cutting process parameters. The study of the surface state and cutting force of the machined surface is the basis of the research on the cutting mechanism.

In this paper, the microstructure and surface state of the 16Co14Ni10Cr2Mo steel were tested during the different milling parameters. We analyze the influence law of each milling parameter on the milling force and in the meanwhile, investigate the effect of the different processing parameters on the surface condition.

With the increase of the depth of the axial milling, the feed rate and the depth of the radial milling, the milling force increases. The milling force is reduced with the increase of milling speed. For ultra-high strength steel 16Co14Ni10Cr2Mo, it is suitable to adopt small cut, high milling speed milling process. After the material surface is milled, the chip can be partly melted. The hardness of the material surface is not increased obviously when the milling speed and feed per tooth increased. Work hardening does not appear on the material surface.

2. Materials and Methods

2.1. Test Method

The basic components of 16Co14Ni10Cr2Mo were analyzed by the chemical analysis method. The mechanical properties were tested by the tensile, and impact test.

Milling experiments were performed in a vertical machining center with 10% of emulsified oil as coolant. The milling force data was tested and recorded by three-Dimensional Dynamometer.

The microstructure and hardness of the sample surface were analyzed by the JSM-7000F JEOL scanning electron microscope (SEM) and Vickers hardness tester before and after the milling process at the different milling parameters.

2.2. Material characteristics

The material adopts forging blank. The pre-processing heat treatment process of the material is high temperature tempering after normalizing. The hardness of the material is HRC35.5. Table 1 shows the composition of the 16Co14Ni10Cr2Mo steel. The mechanical properties are summarized in Table 2.

| Element | C  | Mn | Si | S  | P  | Cr |
|---------|----|----|----|----|----|----|
| wt.%    | 0.16 | 0.054 | 0.025 | 0.0012 | 0.0052 | 1.97 |
| Ni      | 9.88 | Co | Mo | Ti | Al | O | N |
| 13.69   | 0.94 | 0.0051 | 0.012 | 0.0012 | 0.0008 |

| Tensile Strength | Yield Strength | Elongation rate | Surface shrinkage |
|------------------|----------------|-----------------|-------------------|
| 1749 [MPa]       | 1711 [MPa]     | 12 %            | 67 %              |
Figure 1 shows the microstructure of 16Co14Ni10Cr2Mo steel, which displays the typical lath martensite.

2.3. Experimental equipment and conditions
The experiment was carried out on a HAAS-VF1 vertical machining center (HAAS Inc., Oxnard, CA, USA). The tool used in the study is a 4-edge end mill H4020017-10-1 (Walter Inc., Tubingen, Germany) made of carbide. Milling force sensor is 9257B three-way dynamic piezoelectric force sensor (Kistler Inc., Shanghai, China). Signal system consists of 5070A charge amplifier (Kistler Inc., Shanghai, China) and data acquisition instrument WS-5921 (Wavespectrum Inc., Beijing, China). The material is made into workpieces for milling experiment by wire-electrode cutting and grinding. The experimental equipment is shown in Figure 2.

3. Results and Discussion
3.1. Milling force
When the test system uses milling parameters with speed $V_c=12.56$, feed per tooth $f_z=0.025$, radial milling depth $a_e=1.0$ and axial milling depth $a_p=10$, the image of instantaneous milling forces $F_x$, $F_y$ are shown in Figure 3, respectively. It is found that the existence of strong volatility for the milling forces because of the intermittent cutting. In order to eliminate the effects of unstable factors in the milling process for the index determination and to record the average changes of milling force under different milling parameters, the sampling frequency in the data acquisition was increased so that a large number of sample number in the data processing was picked up.
Figure 4 shows Relationship between milling force and milling parameters. From Figure 4(a), it can be found that the milling force obtained with the change of radial milling depth $a_e$ at the milling parameters of speed $V_c=15.7$ m/min, feed per tooth $f_z=0.03$ mm, axial milling depth $a_p=10$ mm. It could be seen that milling forces at different directions, $F_x$, $F_y$ and $F_z$, increase with the increment of radial milling depth. A near linear relationship between them displays. Wherein, the radial milling force $F_y$ increases greatly, and the tangential milling force $F_x$ and the axial milling force $F_z$ increases a little. The reason might be the increment of the milling angle between the tool and the workpiece improves the milling area with the deeper radial milling depth so that the friction between the tool and the workpiece increases and the radial milling force $F_y$ increases simultaneously.

From Figure 4(b), it can be found that the effect of the axial milling depth on the milling forces at the cutting parameters of milling speed $V_c=15.7$ m/min, the feed rate per tooth $f_z=0.03$ mm, the radial milling depth of $a_e=10$ mm. It can be seen that $F_y$ and $F_x$ increase with the increment of the axial milling depth $a_p$. Both linear trend is basically similar with relationship between milling force and
radial milling depth. However, the axial milling force $F_z$ decreases with the axial milling depth, which might come from the cutting edge of the cutter increased with the increment the axial milling depth. With the axial stability of the tool improving, the axial vibration and the axial milling force reduce.

The effect of feed per tooth $f_z$ on the milling force is shown in Figure 4(c). The milling parameters are the milling speed $V_c = 25.12$ m/min, axial milling depth $a_p = 10$ mm, radial milling depth $a_e = 0.5$ mm. It could be found that all the $F_x$, $F_y$, and $F_z$ increase with the increment of the feed per tooth. $F_x$ increases more quickly but the change of $F_y$ and $F_z$ is not very obvious. The reason might be that while the feed per tooth $f_z$ increases, the unit time to participate in the cutting area increases so that the cutting thickness increases and therefore the milling force increases simultaneously. Compared with $F_x$, whose direction along the cutting direction, the effect of $F_z$ was more significant.

Figure 4(d) shows the test results for the effect of milling speed $V_c$ on the milling force. It can be found that all $F_x$, $F_y$, and $F_z$ decrease with the increment of milling speed $V_c$ and the decreasing slope is bigger for $F_x$ than those of $F_y$ and $F_z$. The results should come from the effect of cutting temperature, which increases with the increase of milling speed $V_c$ and induces the decrease of the cutting resistance and the cutting force.

These results illustrates that the milling force increases with the increment of the axial milling depth, the feed per tooth and radial milling depth but reduces with the increase of milling speed. Among of them, the effect of axial cutting depth on the tangential cutting force is far significant than those of other cutting parameters. On the other hand, all the measured cutting parameters have remarkable influence on the radial cutting force $F_y$, especially the radial cutting depth and the axial cutting depth. For axial cutting force $F_z$, the effect of axial milling depth is more significant.

3.2. Surface microstructure under different milling parameters

![Fig.5 Surface morphology after milling in different milling speed $V_c$](image)

![Fig.6 Surface microstructure after milling](image)
Figure 5 and Figure 6 shows the surface morphology after milling in different milling speed $V_c$, in which figure 5(a) shows the surface morphology after milling at the milling speed $V_c=15.7$ m/min, feed per teeth $f_z=0.04$ mm, axial milling depth $a_p=10$ mm, radial milling depth $a_e=0.5$ mm, figure 5(b) shows the surface morphology after milling at the milling speed $V_c=25.12$ m/min, feed per teeth $f_z=0.04$ mm, axial milling depth $a_p=10$ mm, radial milling depth $a_e=0.5$ mm.

1) After milling, some elements of the surface has melted, which shows the high cutting energy. From figure 6, it can be found that the surface of material has melting ball after milling. At high temperatures, when the chip is separated, some elements is melted and adhered to the machined surface to form a molten ball. From material characteristics, it can be seen that the ultra-high mechanical properties make it produce high cutting energy when the chip is separated, and the high temperature leads to the melting of some elements.

2) With the increase of milling speed, the melting material is increased. In Figure 5, feed per tooth $F_z$, axial depth of cut $a_p$ and radial depth of cut $a_e$ unchanged, and milling speed $V_c$ is different. There were melting ball in figure, melting balls per unit area in (d) the number more than (b), shows that with the milling speed increases, the friction of tool with the material increased, the cutting zone temperature increases, cutting higher energy, thus increasing the melt.

3.3. hardness of the milling surface
When the material is in plastic deformation, the grain is elongated, broken and fibrotic because of the slippage and dislocation of the grain. It will increase the hardness of the surface of the material, that is, the work hardening. Figure 7 shows the Vickers hardness of the surface after milling.

![Graph](image)

Fig.7 Relationship between hardness of the cutting surface and milling parameters: (a) $V_c$; (b) $f_z$

From figure 7, it can be found that with the increase of cutting speed and feed rate, the surface hardness is not increased obviously, no work hardening obviously after the milling. The ultra-high mechanical properties of the material make the bonding force between atoms strong, and the plastic deformation stage of the material is very short. There are almost no plastic deformation and lattice distortion when the chip is separated. The grain is not strengthened in the milling. As a result, the surface material is not working hardened.

4. Conclusion
The milling performance of 16Co14Ni10Cr2Mo steel and its influence on the surface condition are studied. Key information is summarized as follows:

1) With the increase of the depth of the axial milling, the feed rate and the depth of the radial milling, the milling force increases. The milling force is reduced with the increase of milling speed.

2) The effect of axial cutting depth on tangential milling force and axial milling force is the most significant. The milling force increases with the increase of the axial milling depth.

3) For ultra-high strength steel 16Co14Ni10Cr2Mo, it is suitable to adopt small cut, high
milling speed milling process.

(4) During chip separation, some elements of the surface has melted.

(5) The hardness of the material surface is not increased obviously when the milling speed and feed per tooth increased. Work hardening does not appear on the material surface.

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