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Technical Paper

Surface finish and affected layer in milling of fine crystal grained stainless steel

Takafumi Komatsu[a], Yuji Musha[b], Tomoaki Yoshino[b], Takashi Matsumura[b,*]

[a] Komatsu Seiki Kosakusho Co., Ltd, Nagano, Japan
[b] Tokyo Denki University, Tokyo, Japan

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ABSTRACT

When the removal depth in micro milling is downsized, the effect of the crystal grain in material becomes relatively large. The crystal grain in materials, therefore, should be downsized to achieve high qualities and high reliabilities of the micro devices. The study discusses the effect of the crystal grain size on the surface finish, burr formation and the affected layer in micro milling of stainless steel. The crystal grains are reduced to an average size of 1.5 μm by repetition of material forming and phase transformation. The milling tests were performed to measure the cutting forces, the surface finishes, the burr shapes and the thicknesses of the affected layers. The force component ratio of the fine grained steel is higher than that of the standard steel. The shearing force decreases in cutting of the fine grained steel; meanwhile, the friction and/or the indentation forces increase. Burr formation is reduced when the crystal grain size is small. In cutting of the standard steel, X component in the cutting force suddenly drops near the end of the groove and a large burr is formed on the edge of the groove. The affected layer largely depends on the crystal grain size. The thickness of the affected layer remarkable decreases in milling of the fine grained steel.

1. Introduction

Micro milling has been applied to manufacturing of micro devices in automobile, medical and bio industries with downsizing of the products. Such milling operations require fine surfaces with high machining accuracies. The cutting processes in the micro milling largely depend on the edge radius of the tool as well as the runout and the dynamic displacement of the end mill. In terms of the material related issues, when the uncut chip thickness is an order of less than 10 μm, which is generally the crystal grain size of the material to be cut, the cutting are not regarded as isotropic process. Chae et al. [1] suggested that the steels consisting of standard crystal grains were regarded as non-homogeneous materials in the micro cuttings. Then, the dynamic components in the cutting forces become relatively large. Liu et al. [2] studied vibrations in machining of homogeneous materials and they associated with the crystallography. Furthermore, the size and the orientation of the crystal grains in the material have an influence on not only the surface finish but also the affected layer in subsurface.

The recent material technology has progressed to improve the mechanical strengths and their uniformities of the materials with reducing the crystal grain sizes. Murty et al. [3] reduced the crystal grain size of 0.15% carbon steel in forming at large strains. Saito et al. [4] developed bulk materials in the roll-bonding processes. Belyajov et al. [9] applied multiple deformations to form fine grained structures in austenitic stainless steels. Kimura et al. [5] studied the changes in microstructures and the mechanical properties with reducing the crystal grain sizes. Umemoto formed a nanocrystaline structure in a large plastic deformation [6]. Ohmari et al. [12] also formed fine-grained structures with repeating the warm caliber-rolling.

When the crystal grain sizes are small compared to the uncut chip thickness, the chip formation becomes isotropic, and consequently, the surface finish is improved with reducing the cutting vibration. Authors studied the effect of the crystal grain size on the cutting mechanism and the surface finish in the micro planing [7]. They reported the dynamic component in the cutting force was reduced with the crystal grain size and the surface finish was improved with controlling burr formation.

As another manner, milling is commonly applied to the practical cutting operations for profiling of the products. Then, burr forma-

* Corresponding author.
E-mail addresses: takafumi@komatsuseiki.co.jp (T. Komatsu), yuji.musha@ezweb.ne.jp (Y. Musha), yoshino@komatsuseiki.co.jp (T. Yoshino), tmatsumu@cck.dendai.ac.jp (T. Matsumura).

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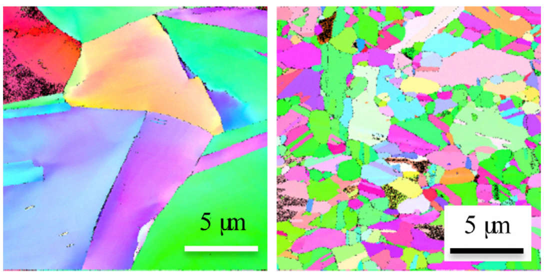
Table 1
Chemical composition.

	Composition %
Carbon (C)	0.06
Silicone (Si)	0.4
Manganese (Mg)	1.09
Phosphorus (P)	0.03
Sulphur (S)	0.004
Nickel (Ni)	8.03
Chromium (Cr)	18.02



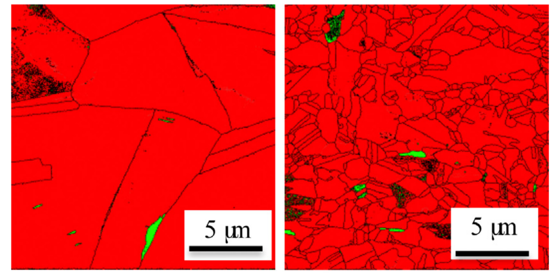
(a) Standard (b) Fine grained

Fig. 1. Crystalorientations: (a) standard and (b) fine grained. (For interpretation of the references to color near the citation of this figure, the reader is referred to the web version of the article.)

tion and the affected layer should be discussed for high quality and high reliability. Especially, the change in the material properties of subsurface is critical in terms of biocompatibility. The paper studies the surface integrity in the micro milling of fine crystal grained stainless steels. Burr formation on the surface and the microstructures in subsurface are observed for the micro grooves machined by milling. Then, burr formation is associated with the change in the cutting force. The affected layer is observed in the cross section of the surface finished. The thickness of the affected layer is also associated with the cutting force in milling.

2. Material properties

The paper discusses Nickel–Chromium stainless steels (X5CrNi18-10, ISO). The materials were manufactured in a heat batch processing [11]. Table 1 shows the chemical compositions of the materials employed in the cutting tests. The standard stainless steel was formed to reduce the plate thickness from 3 mm to 0.2 mm in rolling with heat treatment, where the average size is 9.10 μm. The fine grained steel was formed to be 1.52 μm with repeating plastic deformation and reverse phase transformation. Fig. 1 compares the microstructure of the materials which is observed by Electron Back Scatter Diffraction (EBSD), where red, green and blue color shows [0 0 1], [1 0 1] and [1 1 1] planes in the crystal, respectively. Fig. 2 shows distribution of α′ and γ crystal phases designated by green and red colors, respectively. Both of materials mainly consist of γ crystal phases. Because all crystal planes are observed in Fig. 1(a) and (b), the materials are regarded as isotropic in a large scale area. However, in a view of 10 μm square area, which is the same grain size in Fig. 1(a), the standard steel is not regarded as an isotropic material any more. The anisotropic properties, therefore, induced by the crystal orientation. Meanwhile, isotropic material behavior is expected in the fine grained steel. Fig. 3 shows the grain size distributions of the materials. The scattering of the grain sizes in the standard steel is much larger than that of the fine grained steel. The scattering induces the unstable process with vibration in cutting.



(a) Standard (b) Fine grained

Fig. 2. α′ and γ phases: (a) standard and (b) fine grained. (For interpretation of the references to color near the citation of this figure, the reader is referred to the web version of the article.)

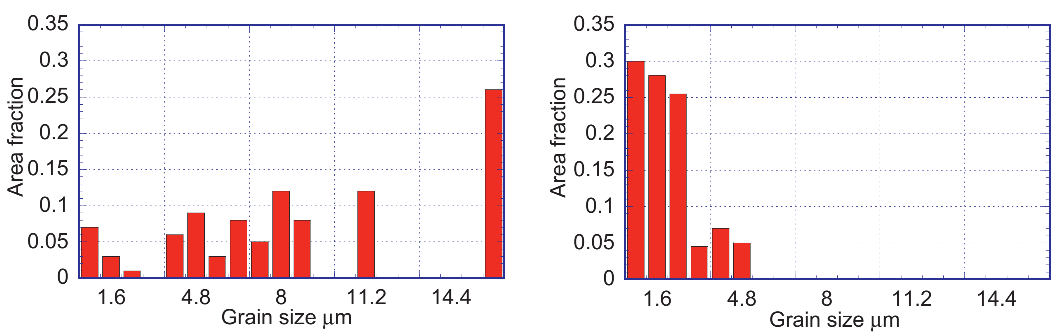
Table 2
Mechanical properties.

	Standard	Fine grained
Vickers hardness (HV)	260	260
Tensile strength (MPa)	870	919
RD	858	880
ND	51.1	42.5
Elongation (%)	57.5	46.4
RD	9.10	1.52
ND	260	260
Ave. grain size (μm)	870	919

Table 2 shows the mechanical properties of the standard and the fine grained steels. Although the grain sizes of the tested materials were different, the tensile stresses of the materials were adjusted to be around 900 MPa.

3. Cutting test

The cutting experiments were conducted to machine grooves with measuring the cutting forces and the surface profiles, as shown in Fig. 4. A piezoelectric dynamometer (Kistler Type 9256C2) was



(a) Standard (b) Fine grained

Fig. 3. Distribution of crystal grain sizes: (a) standard and (b) fine grained.