Journal of Manufacturing Processes 14 (2012) 126–134

Contents lists available at SciVerse ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Technical paper

Orthogonal machining of single-crystal and coarse-grained aluminum

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ARTICLE INFO

Article history:
Received 21 October 2011
Received in revised form 19 January 2012
Accepted 31 January 2012
Available online 4 April 2012

Keywords:
Machining
Micro-machining
Single crystal
Coarse grained polycrystals
Microstructure
Anisotropy
Orthogonal cutting
FIB-OIM
Subsurface deformation

ABSTRACT

Orthogonal machining of single-crystal and coarse-grained (i.e., grain size considerably larger than the uncut chip thickness) materials has been a subject to many studies in the literature. The first part of this paper presents background on machining single-crystal materials, including experimental and modeling attempts. The second part briefly describes more recent modeling results from the authors, and presents new experimental results on planing and plunge-turning of single-crystal and coarse-grained aluminum using diamond tools. The experiments indicate that (1) cutting across grains of a coarse-grained aluminum workpiece produces distinctly varying forces and surface roughness from one grain to another, (2) plunge-turning and planing of single crystal aluminum provide equivalent force data for large rake angles, (3) forces alter between two distinct levels while cutting single crystals with small rake angles, and (4) with small rake angles, subsurface damage on single-crystal aluminum is extensive, reaching depths comparable to the uncut chip thickness.

1. Introduction

Machining of single-crystal and coarse-grained materials is of interest due to (a) the demand from various applications for single-crystal parts due to their uniformity and reduced level of defects (e.g., turbine blades, precision mirrors), (b) the need for developing fundamental understanding of materials and material removal, since all crystalline materials are composed of grains and grain boundaries, which, to a large extent, dictate their mechanical properties. Recent interest in ultra-precision machining and micro-machining also motivated single-crystal machining analysis, since those processes include chip-thicknesses commensurate with the grain size of many engineering materials, making crystallographic anisotropy critical in machining response.

The first part of this paper provides extensive background on machining of single-crystal materials, including brief descriptions of authors' work. In the second part, new experimental results on planing and plunge-turning of single-crystal and coarse-grained aluminum are presented. The experimental apparatuses used for planing and plunge-turning experiments are described in detail. Planing experiments are conducted on coarse-grained aluminum, and forces and surface roughness across the grains are analyzed. Next, plunge turning and planing of single-crystal aluminum are compared. Subsequently, the extent of subsurface damage during plunge turning of single-crystal aluminum is analyzed.

2. Background

2.1. Experimentation on machining of single-crystal and coarse-grained materials

A number of experimental studies have confirmed that machining response including machining forces [1–12], chip lamellae [1,13–16], dynamic shear stress [2–6], and surface roughness [4,7,10] strongly depend on the crystallographic orientation in fcc metals. Some investigations also considered the effect of crystallographic anisotropy on the built-up edge (BUE) [13] and material side-flow [10]. Researchers have conducted both plunge-turning [3,4,12] and planing experiments [2,5–11,13–16] on single-crystal metals. Some of the experimentation was conducted inside a scanning electron microscope (SEM), allowing visual observation of chip formation [3,16]. Single-crystal fcc materials, mainly aluminum [1–4,8–11], and copper [3,5,6], have been tested in these studies. Table 1 tabulates the cutting conditions and materials considered in some of the works in the literature.

Early studies on machining single crystals were aimed at observing the lamellae structure of the chips formed during machining.

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1526-6125/$ – see front matter © 2012 Published by Elsevier Ltd on behalf of The Society of Manufacturing Engineers.
doi:10.1016/j.jmapro.2012.01.002

Table 1
Experimental studies on single-crystal machining from the literature, and associated machining parameters.

	Material	Rake angle	Feed (μm)	Speed (mm/s)
Clarebrough and Ogilivie [13]	Pb	60°	25	–
Black [14]	Cu, Al	–	0.0025–2	1
Ramalingam and Hazra [2]	Al	40°	127	0.27
Williams and Gane [6]	Cu	40°	1–100	0.1–1
Ueda and Iwata [16]	β-brass	0°, 20°	0.1–200	0.0025
Williams and Horne [5]	Cu	40°	100	20
Cohen [3]	Cu, Al	50°–0°	114.3	0.44
Sato et al. [8–10]	Al	35°	100	1.66
Sato et al. [11]	Al	3°	0.5–3	16.66
Moriwaki et al. [7]	Cu	0, 5°	0.01–3	8833.33
Yuan et al. [12]	Cu, Al	0°	1–10	0.16–0.83
To et al. [4]	Al	0°	1–10	0.16–0.83
Zhou and Ngoi [17]	Al, Cu	0°	5–10	1300
Lawson et al. (2007) [1]	Al	0°	5–20	5–15

The first known study was published in 1950 by Clarebrough and Ogilivie [13], who microtomed large crystals of lead and observed a strong correlation between the crystallographic orientation and lamellae spacing. Subsequent studies of Black and von Turkovich shed light on various aspects of micro-scale chip formation in single-crystal cutting [14,15]. They performed a quantitative study of chip formation mechanisms in single-crystal copper and aluminum via an ultra-microtomy process. The lamellae thickness was seen to be affected by the crystallographic orientation and uncut chip thickness (below 2 μm) [14].

Of all the machining responses, the variation of machining forces (and therefore the specific energies) while cutting single-crystal materials at different orientations have been studied in greater detail by various researchers [1–3,5–12]. A majority of the researchers [1,5–11] used the planing configuration, in which the tool cuts along a particular crystal direction for a fixed length of the workpiece (see Fig. 1(a)). The planing data on aluminum consists primarily of cutting forces on (1 1 1) [6,10,11], (1 1 0) [6,10,11] and (0 0 1) [9,11] planes ([*u v w*] in Fig. 1(a)). Planing force data was also collected for cutting various directions about [0 0 1] [1] and [1 1 2] [10] zone axes on aluminum single crystals (i.e., the zone axis directions coincide with [*a b c*] in Fig. 1(a)). The planing forces on copper have been measured while cutting on (1 1 0) and (1 1 1) planes [6], and about [1 − 10] zone axis [5,7]. The results from the planing studies showed that the anisotropy of fcc crystals strongly affects the machining forces, inducing up to 312% variation in machining forces at different crystallographic orientations for a given zone axis [1]. The magnitude of variation in machining forces must be contrasted with results from nanoindentation, where the dependence of hardness on orientation is observed to be minimal [25]. For example, the observed variation in hardness in copper, between {1 1 0} and other surfaces was 6%.

In addition to constant (stable) machining forces [1,2,6–8,11], monotonically-increasing [8], bi-stable [1,6] and periodically-varying [1,16] force signatures have been observed for different cutting parameters and crystallographic orientations during planing experiments. Abrupt, short-term reduction in forces was also observed in some studies [8].

While planing experiments provide detailed data in terms of cutting forces, only one crystal orientation can be machined at a time. As an alternative to the planing configuration, the plunge-turning configuration shown in Fig. 1(b, c) has been used in [3,4,12]. This configuration provides near-continuous data for the entire range of cutting directions for a given zone axis. These turning experiments can be further divided into two types. Whereas Fig. 1(b) shows the case where the zone axis [*a b c*] serves as the axis of rotation, Fig. 1(c) has the cutting plane normal as the axis of rotation. Henceforth, the case shown in Fig. 1(c) will be referred to as in-plane machining for clarity.

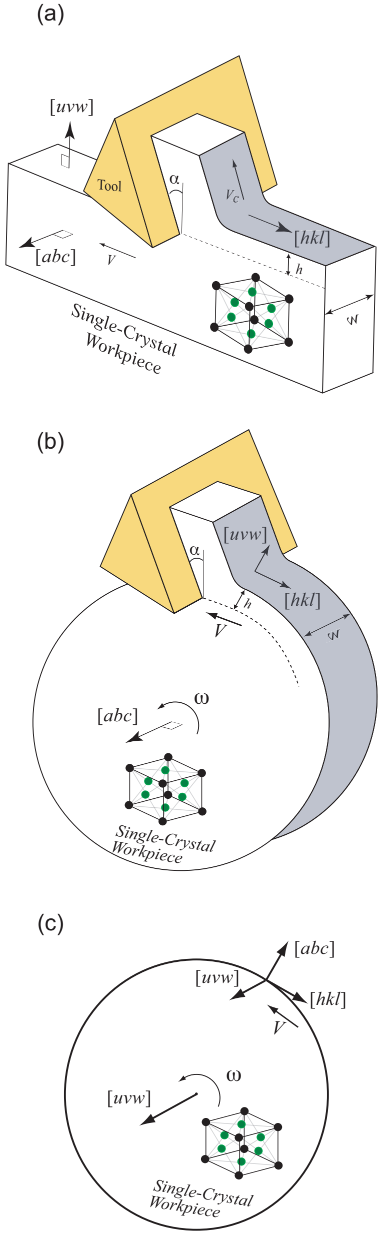

Fig. 1. (a) Planing configuration, (b) plunge-turning configuration, and (c) in-plane machining.

In the plunge turning experiments of Cohen [3], cutting forces were collected about the [0 0 1] zone axis ([*a b c*] in Fig. 1(b)) while cutting both aluminum and copper single-crystals. The force measurements from these experiments showed a repeatable four-fold symmetry expected from the crystallographic symmetry of [0 0 1] zone axis. While the [1 0 0] cutting direction produced the minimum force, the maximum force was consistently observed to occur at an offset of 15–20° from [1 1 0] cutting direction.

The in-plane machining results [4,12] consist of machining force variation with cutting directions about (1 1 0) and (1 1 1) cutting plane normals. The experimental force variation with cutting directions on (1 1 0) plane were found to be larger than those on (1 1 1) cutting plane due to the increased crystallographic symmetry on (1 1 1) plane as compared to (1 1 0) plane.

Apart from the machining forces, another important machining response is the roughness of the machined surface. Experimental