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Validation of the cutting equation by accurate orthogonal cutting experiments

Hiroo Shizuka[1], Katsuhiko Sakai[1], Jinya Yoshida[1], Kenichi Ishihara[2], Yoshihiro Kawakami[2]

[1]Shizuoka University,3-5-1 Johoku Naka-ku Hamamatsu Shizuoka 432-8561 Japan
[2]Johoku Industrial Co.Ltd, 1092 Kamiarayacho Higashi-ku Hamamatu Shizuoka 435-0053 Japan

shizuka.hiroo@shizuoka.ac.jp

Abstract

This study focuses on accurately measuring orthogonal cutting experimental values to validate cutting equations. Attempts were made to measure these values using a newly developed dedicated orthogonal cutting machine to validate previously proposed cutting equations. The experiment involved selecting a workpiece material that would generate continuous chips without forming a built-up edge or burr under a range of cutting conditions. This material was then used to conduct orthogonal cutting experiments. The experimental values obtained in this study were found to be relatively close to previous experimental values at high cutting speeds but deviated significantly at low-speed and micro cutting conditions. The dependency of experimental values on cutting speed was noted, highlighting the necessity of considering this factor in establishing accurate cutting equations.

Orthogonal cutting, cutting theory, cutting equation, shear surface theory

1. Introduction

When studying cutting phenomena, it is crucial to understand the chip formation mechanism. To address this, many studies have investigated mechanical solutions using orthogonal cutting models, and cutting theories, particularly shear plane models, have been developed since the 1930s. The primary purpose of shear plane theory is to calculate the shear angle, and numerous cutting equations have been proposed to date. Although these equations qualitatively display trends similar to experimental values, large quantitative errors are often noted [1]. Additionally, various issues have been raised concerning the experimental values used to validate theory. These include inadequate implementation of precise orthogonal cutting, deviation of cutting conditions from those used in actual machining, and many experiments being conducted several decades ago with measurement accuracy problems. Therefore, the need to validate the accuracy of experimental values is evident. In response, some studies have reported the development of a orthogonal cutting machine for use in relevant experiments [2]. However, many such experimental devices struggle with issues related to cutting speed and device rigidity, hindering the achievement of accurate orthogonal cutting under general conditions. Hence, this study developed a new orthogonal cutting machine to obtain precise experimental values. This device was initially used to select a workpiece material that would produce continuous chips without forming a built-up edge across a broad range of cutting speeds, from ultra-low to high, thereby facilitating the validation of shear plane theory. Subsequently, experimental values for orthogonal cutting were measured using this material and compared with previously reported values. Additionally, various cutting equations were evaluated against these experimental values to ascertain the accuracy of the cutting equations.

2. Experimental setup

In this study, a orthogonal cutting machine (Figure 1: left) was built for accurate orthogonal cutting. This device had two linear motors and was capable of machining and cutting speeds of 0.001 m/min–180 m/min (±0.5%) with full feedback control using a linear scale. The device also had a rigidity that could withstand over 1000 N in both the cutting force direction and thrust force direction. The tool holder has a drive mechanism with planetary gears and a vernier that enables fine adjustment of the depth of cut. Cutting force can be measured using a dynamometer (Kistler type9601A) built into the tool holder, as shown in Figure 1 (right), and temperature can be measured with the tool-workpiece thermocouple method using the workpiece material and wiring attached to the tool. Furthermore, the cutting points can be freed to enable observation using a high-speed camera.

Figure 1. Orthogonal cutting machine

3. Selection of workpiece material

Selecting a workpiece material that avoids built-up edges or burrs during machining and can generate continuous chips under a wide range of cutting conditions is crucial for obtaining accurate experimental values to validate cutting equations. Consequently, cutting experiments were conducted using eight types of aluminum alloys listed in Table 1 at cutting speeds ranging from 0.01 to 180 m/min. Materials that met the above criteria were selected. Figure 2 shows an example of the experimental results at a rake angle of 5°. The figure illustrates that 5052 (180 m/min), 5083 (10 m/min), and 6063 produce built-up cutting edges, shear-type chips, and burrs. Table 2 summarizes these findings. ANP79 exhibited no built-up edge at cutting speeds ranging from low to high and generated continuous chips. Based on these results, ANP79 (7075T651) was selected as the workpiece material.

Table 1 Cutting conditions

Work material (AISI)	2017, 2024, 5052, 5083, 6061, 6063, 7075T651 (ANP79), 7075
Cutting speed *V* [m/min]	0.01, 0.1, 1, 10, 180
Depth of cut[mm]	0.10
Cutting width[mm]	2
Rake angle[°]	-10, -5, 0, 5, 10

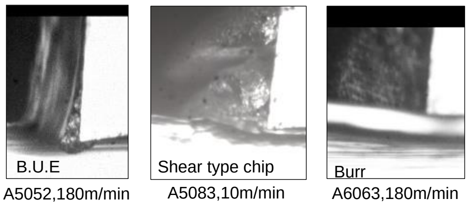

Figure 2. View of the near cutting point using a high-speed camera

4. Validation of experimental values for orthogonal cutting

Merchant, Shaw, and Oxley equations are particularly well-known among the various cutting equations proposed to date, and they have all evaluated the accuracy of their equations by comparing them with their experimental values [3]. As Figure 3 illustrates, the results were categorized into two groups: the 100–200 m/min cutting speed conditions by Merchant et al. and the ultra-low speed conditions of 0.01–0.02 m/min by Shaw, Cook, and Finnie, as well as by Oxley et al. However, the accuracy of these experimental values has been questioned due to outdated machine tools and measuring instruments, necessitating further validation. Figure 3 also presents the results of cutting experiments conducted using the newly developed orthogonal cutting machine across ultra-low to high-speed conditions. The figure shows that, despite a change in cutting speed by a factor of 10,000, the measurement results were consistently within a close range, aligning with the values from Merchant and Lapsley et al. Conversely, the experimental results from the present study differed significantly from those of Shaw, Cook, and Finnie or Oxley et al. This discrepancy is likely attributed more to the cutting environment than the cutting speed, given that the experiments were conducted in an SEM with micro cutting conditions such as depth of cut. Furthermore, it is widely known that the experimental values are distributed

Table 2 Relationship between cutting conditions and chip formation

AISI \ m/min	180	100	10	1	0.1	0.01
2017	B.U.E.					
2024	○	B.U.E.				
5052	B.U.E.			Burr		
5083	B.U.E.		Shear type chip			
6061	○	B.U.E.				
6063	Burr					
ANP79	○	○	○	○	○	○
7075	○	B.U.E.				

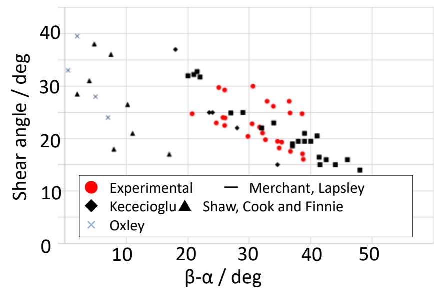

Figure 3. Comparison of experimental values for several orthogonal cutting

around the middle of the Merchant and Lee-Shaffer cutting equations. However, focusing on the experimental results of this study, as depicted in Figure 4, it is evident that the values were categorized into two groups: one with cutting speeds of 100 m/min or higher, and another with speeds of 10 m/min or less. This distinction is attributed to the fact, as illustrated in Figure 5, that the temperature remained close to room temperature at cutting speeds of 1 m/min or less, while the cutting temperature significantly increased at speeds of 100 m/min or higher. Mechanical properties such as tensile strength and fracture toughness of 7075 have temperature and strain rate dependence [4]. This is considered to be the reason why the cutting forces showed a speed dependence. This observation suggests the need to incorporate a temperature term into the cutting equation. Additionally, it was observed that the values closely matched the Merchant and Krystof equations at cutting speeds of 100 m/min or higher.

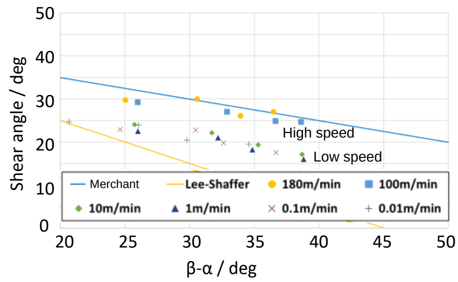

Figure 4. Relationship between cutting speed and shear angle

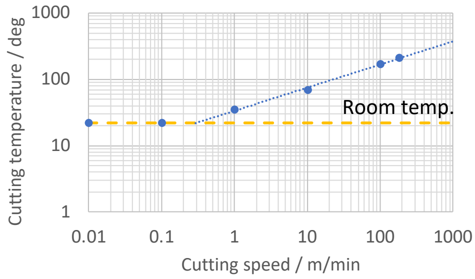

Figure 5. Cutting speed and cutting temperature

5. Summary

This study aimed to accurately measure orthogonal cutting experimental values, necessary for validating cutting equations, using a newly developed orthogonal cutting machine. The results demonstrated that a material capable of producing continuous chips without forming a built-up edge or burrs could be selected, even when significantly altering the cutting speed. Additionally, when conducting orthogonal cutting experiments with this material, it was found that the Merchant experimental values were more accurate compared to the various reported experimental values. It was also found that the obtained experimental values were dependent on the cutting speed, and therefore, the temperature dependency should be considered in the cutting equation.

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