Development of High-speed Shearing Method to Obtain Flow Stress under High Strain Rate

Norfariza Wahab, Hiroyuki Sasahara, Shinnosuke Baba, Yuta Hirastuka, and Takashi Nakamura

***Abstract*—It is well known that a numerical simulation technique can be used to predict machining states such as cutting forces, stresses and temperature distribution. However, it is critical to simultaneously estimate the stress-strain relationship of the workpiece, and the friction characteristics between tool-chips during high-speed cutting processes. The objective of this study was to develop a new high-speed shear-slitting method that could at the same time neglect friction between tool-chip deformations. Through the proposed method, high-speed deformation characteristics of workpiece flow stress applicable for FEM simulation can be obtained. In this study, the Johnson-Cook (JC) constitutive equation flow stress model was considered as a function of strain, strain rate and temperature under a high strain rate during a shear-slitting process. As a result, we developed a high-speed shear-slitting method that can achieve high strain rates of up to 3.67x10^4 s^{-1}. We then propose a method for deriving the JC constitutive equation from the shear-slitting experiment and two-dimensional simulation of shearing process.**

***Index Terms*—Constitutive equation, flow stress, numerical simulation, shear-slitting.**

I. Introduction

Recent research shows that to obtain an optimum understanding of various cutting conditions, such as speed, feed, chip deformation, etc., it is useful to simulate the real cutting process using FEM simulation. FEM is a recognized method of analyzing cutting-process conditions. To estimate the real cutting process using FEM simulation, material properties of the workpiece are required. Most researchers have suggested that to estimate material properties, the flow stress of the workpiece must be understood [1]-[4]. However, it is almost impossible to estimate the flow stress of the workpiece and the friction between tool-chip deformation at the same time. Tugrul [5], [6] and Hyunjoong [7] tried to estimate flow stress and friction during cutting using FEM simulation, but their results were unsatisfactory.

The stress-strain relationship is an important element of material properties. Stress-strain relationships affect cutting force, chip deformation and temperature. For a high strain rate and high temperature range, it is necessary to determine the stress-strain relationship [1], [2].

To be useful in FEM cutting simulations, flow stress data must be obtained at high strain rates (up to 10^6 s^{-1}) and high temperatures (up to 1000 ℃) as well as strain (up to 4) [8]. These data are difficult if not impossible to obtain reliably with conventional tensile and compression tests. The most popular method for measuring stress-strain relationships at high strain rate is the Hopkinson bar method. However, the strain rate range that can be achieved with this method is only 10^2～10^4 s^{-1}, whereas the effort required is very large and complex.

As a result, there is high demand for data on the stress-strain relationship and friction characteristics during the cutting process that can be applied to FEM simulations. In this study, a new high-speed shear-slitting method was developed. This new method can achieve a strain rate range at high-speed cutting speeds of around 10^3～10^4 s^{-1}. Thus, during FEM simulation, tool-chip friction calculation can be treated as negligible, because the relative speed of the tool and workpiece is assumed to approach zero.

The first objective of this study was to develop a new high-speed shear-slitting method able to realize high strain rate deformation. The second was to propose a methodology for identifying the stress-strain relationship using two-dimensional (2-D) punching shear simulations.

II. Methodology

A. Method for Identification of Stress-Strain Relationship during High Strain Rate Deformation

As a method for deriving the stress-strain relation in a high strain rate range, the constitutive equation of Johnson and Cook [11] is often applied, as shown in Eq. (1) .

In the constitutive model of Johnson and Cook, σ is the stress (MPa), ε is the strain, ε is the strain rate (s^{-1}), T is the temperature (℃), and A, B, C, n, and m are the material flow stress parameters.

$$(A+B\varepsilon^{n})(1+C\,ln\dot{\varepsilon})(1\text{-}T^{*m}) \quad (1)$$

A: yield stress	B: strain hardening constant
ε: plastic strain	n: hardening exponent
C: strain rate constant	ε^{n}: plastic strain rate
T: temperature	

It is possible to conduct a compression test at room temperature, and to determine low strain rate with respect to the coefficients of A, B and n. However, it is not easy to conduct the test with the varying strain rates and temperatures necessary to identify how the coefficient C relates to strain rate, or the coefficients of m to temperature. Using Eq. (1), Norfariza (4) proposed C and m by a reverse

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calculation method. They compared the principal force of the high-speed experimental orthogonal cutting result with the principal force calculated by the FEM simulation. However, results were inadequate, and the calculation of the FEM simulation was time consuming. Thus, it was not possible for the friction coefficient effect to be treated as negligible during the calculation of the FEM simulation.

In this study, a high-speed deformation test method was proposed using a slitting processing for cutting. Fig. 1 provides an overview of the slitting process, which cuts sheet material in the longitudinal direction by rotation of a round blade tool pair of upper and lower rollers. By shearing the material, the tool is rotated. The relative speed of the tool and workpiece is zero. Even at the point where the material is sheared at the high-speed tool, it is possible to ignore the friction between tool and workpiece.

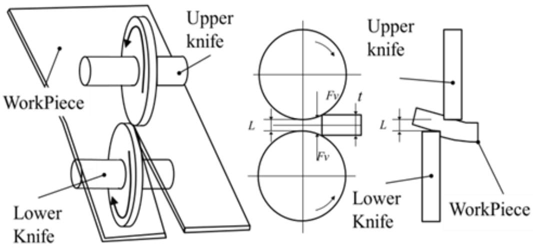

Fig. 1. General slitting process.

B. Newly Developed Shear-Slitting Machine

The same slitting process method was applied in the newly developed machine. Fig. 2 is an enlarged view of the working point near the test apparatus developed in this study. The test apparatus used two rollers for the rotating circular blade tool. Workpieces to be sheared were fed into the overlap portion of the two rollers in the z-axis direction. A thin disk-shaped workpiece was attached using a special jig in the main shaft.

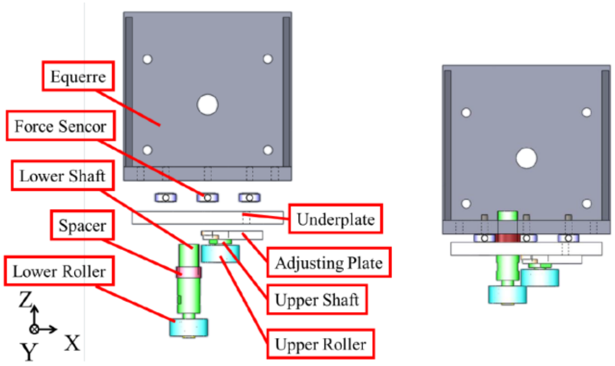

Fig. 2. Enlarged illustration of developed machine.

Fig. 3 shows the workpiece and the shear-slitting machine from above. A piezoelectric dynamometer capable of detecting *x*-, *y*-, and z-axis forces was set beneath the slitting unit. The piezoelectric dynamometer was connected to the charge amplifier and data-acquisition system to measure the force. A force in the x-axis direction component corresponding to the shearing force was applied to the lower roller of the working force (i.e., slitting).

Fig. 4 is a photo of the experimental setup of the shear-slitting machine on an NC lathe machine (Washino C5). The workpiece was attached to the chuck of the NC lathe machine, and sheared into the edge intersections of the upper and lower rollers. The connection to measure shearing force for the experiment traveled from the piezoelectric dynamometer to the charge amplifier, and then to the PC.

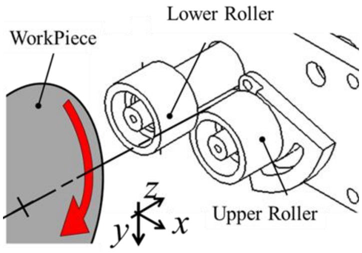

Fig. 3. Views of workpiece and machine setup.

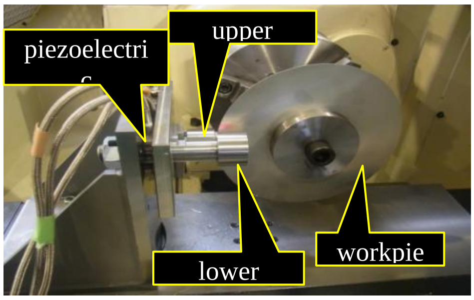

Fig. 4. The experimental setup set on a NC lathe machine.

C. Shear-Slitting Machine and Results

In this study, a number of experimental parameters were considered. Table 1 lists the experimental parameters. As this shear-slitting machine is new, many parameters of materials flow stress remain unknown. In order to investigate the effect of slitting, different clearance and spindle rotation speeds were tested as parameters for the experiment.

We used slitting condition 1 as a reference condition for this experiment. Slitting conditions 2 and 3 had the same clearance but different spindle rotation speeds, while slitting conditions 4 and 5 had the same spindle rotation speed and different clearances. The results of this experiment assumed a steady state situation of the slitting process by evaluating the average value of the machining before the end of 1 s. The working force of the measured x-axis direction was defined as the shearing force. Fig. 5 presents the experimental results in terms of the relationship between spindle speed and shearing force.

TABLE I: SLITTING CONDITIONS OF EXPERIMENTS

No.			1	2	3	4	5
Spindle speed	n	min^{-1}	120	30	240	120	
Clearance	c	mm	0.05			0.04	0.15
Feed rate	f	mm/rev	1				
Rake angle	θ	degree	45				
Workpiece radius	R	mm	220				
Workpiece thickness	d	mm	0.5				
Roller radius	r	mm	22.5				
Circumferential speed	v	mm/sec	1.38×10^3	6.91×10^2	2.76×10^3	1.38×10^3	
Strain rate	$\dot{\gamma}$	s^{-1}	1.82×10^4	4.55×10^3	3.67×10^4	2.27×10^4	6.06×10^3

In comparing experimental conditions 1, 2, and 3, the change in shearing force due to the magnitude of the spindle speed was observed. A comparison of experimental conditions 1, 4, and 5, investigated shearing force with respect to the size of the clearance; here it can be seen that the variation of measured values was small. By comparing the experimental and model results from changing the parameters of clearance in the simulation of the 2-D shear, it is possible to examine the validity of the analysis. The value of $10^3 \sim 10^4$ s^{-1} orders are feasible calculating the strain rate average in the deformation zone of the specimen using the relationship specimen dimensions and axial rotation speed such as roller dimensions and clearance generated by cutting. The method is adaptable to a high strain rate range of cutting processes.

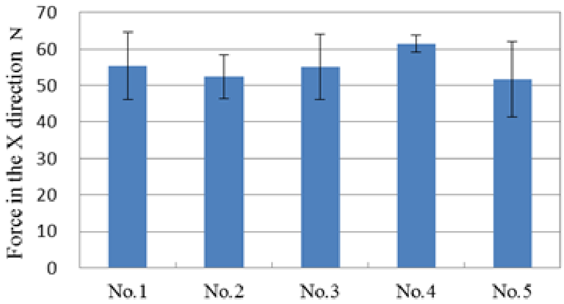

Fig. 5. Relationship between spindle speed and shearing forces.

D. Comparison of Shear-Slitting Method and 2-D Simulations

The movement distance in the *x*-direction of the tool was defined as stroke s. Slitting was divided into minute widths, dy. It was assumed that punching shear stroke was performed simultaneously. Fig. 6(a) shows the deformation of the slitting of the workpiece; Fig. 6(b) shows the replacement of those values with a 2-D punching shear simulation.

It was possible to determine the shearing force at each stroke divided by the 2-D punching shear simulation, by totaling the shearing force and comparing it with experimental results.

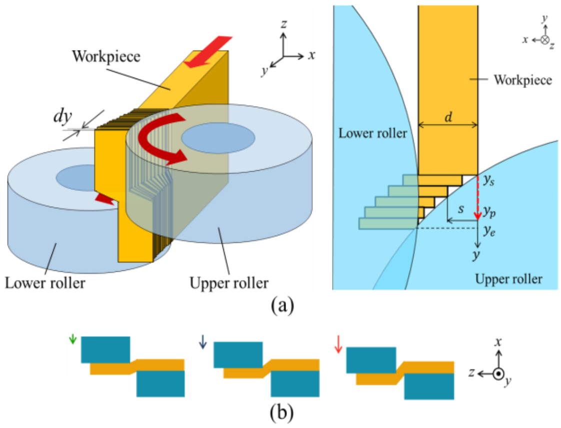

Fig. 6. Schematic of slitting and substitution for 2-D shearing.

An example of a 2-D punching shear simulation is shown in Fig. 7. Fig. 8 presents the slitting force obtained in the simulation with difference clearances for slitting conditions 1, 4 and 5. In this case, the thicknesses in the y-direction were all unit thicknesses (1 mm). From Fig. 8, it may be seen that when the clearance increased, the slitting force decreased.

E. Comparison of Results and Discussion of the Experiment and FEM Simulation

Experimental slitting conditions 1, 4 and 5 from the 2-D punching shear were calculated based on the corresponding clearance. Slitting force, *fx*, per unit thickness corresponding to a stroke s were obtained and are shown in Fig. 9. When replacing the slitting, it was necessary to determine the split in the y-direction of the unit length slitting force per $f_x(s)$. The position of the y-direction shear starts y_s, and y_e is the end position. If the position in the y-direction of any of the dividing planes is defined as y_p, y_p, roller radius r, and roller angle θ , are expressed as follows using stroke s.

$$Y_p = \sqrt{r^2 - (s - r\cos\theta)^2} - r\sin\theta \tag{2}$$

From equation (2) slitting force per unit thickness in y_p can be expressed as f $f_x(y_p)$ dy, which is the shear force per divided micro width. This can be compared with the measured values of experiments by replacing the slitting. The shearing force is then expressed by the following equation.

$$F_x = \int_{y_0}^{y_1} f_x(y_p)dy \tag{3}$$

Values for y_e were determined from the shear zone in the thickness direction of the workpiece. Fig. 9 is a comparison of the slitting force by simulation and experiment. The simulations used the experimental replacement shearing force.

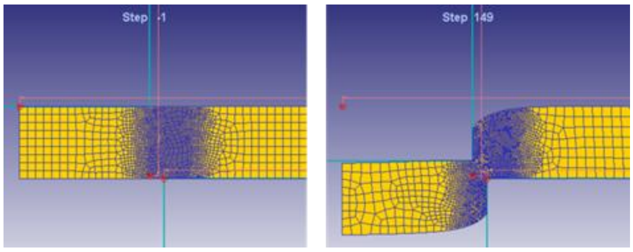

Fig. 7. Two-dimensional punching shear simulation.

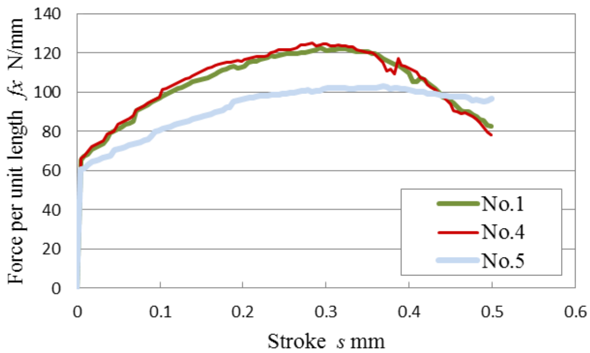

Fig. 8. Simulated force per unit length.

Like the experimental results, the slitting force obtained by simulation had a larger tendency of force as the clearance was reduced. In addition, simulation results under all slitting conditions produced smaller slitting forces than the experimental results. This may have been due to the workpiece undergoing bending effects other than shearing, such as the shearing force measured during the workpiece in the experiment.

F. Identification of flow Stress from Shear-Slitting Method

First, a tensile test was carried out to identify the *A*, *B* and *n* value of flow stress parameters. The workpiece used for testing purposes was A5052, size pattern JIS 13B. The workpiece was 0.5 mm thick. Results of the tensile test for A5052 obtained the following parameters: *A* - 199.1, *B* - 102.6, and *n* - 0.23.

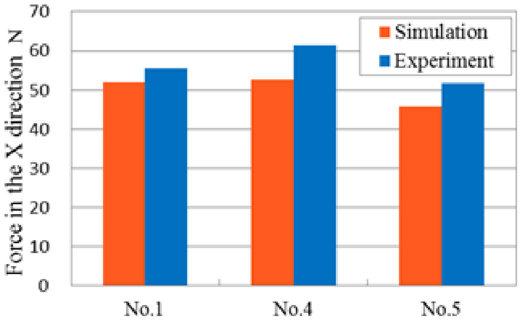

Fig. 9. Force in the x-direction by simulation and experiment.

The determined material constants *A*, *B*, and *n* were used to identify the material constant *C*, and *m*, the flow stress of the Johnson-Cook method, using the shearing force determined by the shear-slitting machine. The initial values of $C = 0.01$ and $m = 1$ were compared with the material constants from the shearing force experiments replaced with the 2-D punching shear models.

Subsequent analyses were the same but changed the value of *C*. It was assumed that the value of *C* nearest to the shearing force would obtain the shearing force of the experiment so it could be compared with a high strain rate range. Analyses of *m* were performed with the same procedure; with the optimal value of *C*, it was possible to identify the *m*. Fig. 10 and 11 show the optimal value of *C* and *m*, respectively, at clearance $c = 0.04$, 0.05 and 0.15. The shearing force, determined by the high speed shear-slitting machine $Fe(i)$, and a shearing force obtained by replacing the simulated values for the three dimensions is set to $Fs(i)$. The evaluation function *R* is defined as the sum of squared residuals for each condition. In this case $i = 1$, 2, and 3 for clearance $c = 0.04$, 0.05, 0.15, respectively.

$$R = \sum_{i=1}^{3} \sqrt{(F_e(i) - (F_s(i)^2} \quad (4)$$

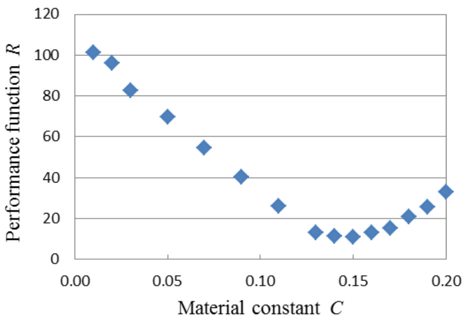

Fig. 10. Identification of optimal material constant *C*.

The evaluation function R is the minimum value *C*, while *m* is the optimum value in the high strain rate range. From this, $C = 0.15$ and $m = 0.96$ were identified. Error between experiment and FEM simulation by the analysis of this material constant becomes 6.45% in the three conditions of clearance. Thus, the accuracy of our proposed method is proved sufficient. Fig. 12 shows the final result for slitting-shear condition number 4 at $c = 0.05$. Form Fig.12 shows that the error between experiment and proposed method is only 1% which is in really good accuracy.

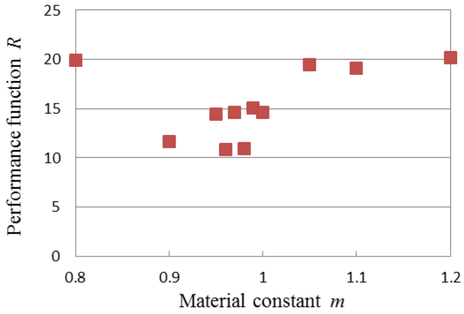

Fig. 11. Identification of optimal material constant *m*.

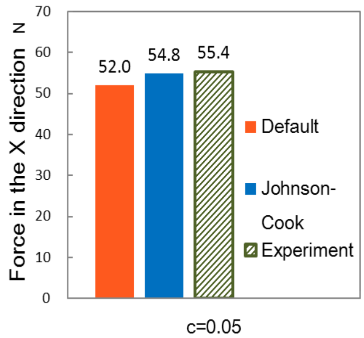

Fig. 12. Force in the X direction by simulation.

III. Conclusions

In this study, a new high-speed shear slitting method that can obtain the high strain rate of deformation characteristics was developed. A method for identifying the stress-strain relationship using 2-D shear-slitting simulations was also proposed. The final stage of this study to identify *C* and *m* was also proposed. As a result, from this proposed method a method to identify flow stress of workpiece under high strain rate had been achieved.

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