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Material testing of copper by extrusion-cutting

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Abstract

An investigation was carried out on the use of extrusion-cutting as a material test method operating at severe conditions of strain, strain-rate and temperature, such as in machining. In extrusion-cutting, a shoe constrains the chip back surface producing a geometrically defined orthogonal cutting process which can be modelled using methods from the theory of plasticity such as, e.g., slip-line and upper-bound. The process was previously proposed for use as a material testing technique to determine the shear flow stress of materials under strains, strain rates and temperatures relevant for analytical modelling of metal cutting. This work represents a new step where the final objective is the generation of stress-strain curves that can be used in analytical models as well as using Finite Element Method (FEM) simulations. A new experimental setup for extrusion-cutting using discs as workpieces was developed and implemented on a CNC lathe. An investigation was carried out extrusion-cutting copper discs using high-speed-steel cutting tools at 100 m/min cutting speed. Flow stress values for copper under machining-relevant conditions were obtained from measurement of the extrusion-cutting force on the tool and application of a simple upper-bound model for the extrusion-cutting process. An attempt to extend the validity of test data to cover a range of cutting conditions was made, and suggestions for improvement of the simple theoretical model given.

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Keywords: Metal cutting; Experimental investigation; Pure copper; Material testing; Extrusion-cutting

Nomenclature

c specific heat
d width of deformation zone
F_c cutting force
F_t thrust force
h tool-shoe offset
J mechanical equivalent of heat
k shear flow stress
L contact length
m= $\cos 2\psi$ friction factor
p=F_c/wt extrusion pressure
S tool-shoe gap
t undeformed chip thickness
t′ chip thickness
T temperature in the deformation zone
v cutting speed
w width of cut
$\dot{W}$ cutting power
Z length of shear plane
α (alpha) rake angle
γ (gamma) shear strain
$\dot{\gamma}$ (gamma dot) shear strain rate
ΔT (Delta T) adiabatic temperature increase
ε (epsilon) equivalent strain
$\dot{\varepsilon}$ (epsilon dot) equivalent strain rate

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θ (Theta) fan angle
λ= t'/t (lambda) chip compression factor
Λ=S/h (Lambda) imposed chip compression factor
ρ (rho) density
σ (sigma) flow stress
τ (tau) shear stress
Ψ (psi) friction angle

1. Introduction

Material testing for use with modelling of machining is particularly tricky and so far no one has been able to develop a technique for determining the flow stress of materials under conditions prevailing in metal cutting, i.e., at high strains, strain rates and temperatures [1]. In literature one can find several approaches for obtaining material data at high strain rates and temperatures, e.g., a Split Hopkinson Pressure Bar (SHPB) complemented with an inductive heat source [2], but they usually cover equivalent strains between 0 and 0.3-0.4 while, during cutting, strains reach values up to 5 [1]. Values beyond test results are then usually extrapolated. A first attempt of using metal-cutting test as a high strain rate material property test at strains larger than those normally achievable in conventional tests was developed by Lira and Thomsen [3] but the approach suffers from the fact that ordinary cutting is characterized by an unrestricted geometry which is difficult to model analytically. This approach was more recently adopted in [4], [5] and [6], and applied to determine work flow stress and friction at tool-chip interface from experimental data for cutting and thrust forces and chip thickness, based on application of Oxley's slip-line field in reverse [7].

In this study we apply the method based on extrusion-cutting previously proposed in [8] and shown in Fig. 1 where a shoe constrains the chip back surface producing a geometrically defined cutting process which can be modelled using methods from the theory of plasticity such as, e.g., slip-line and upper-bound, Fig. 2. The process was proposed for use as a material testing technique to determine the shear flow stress of materials under strains, strain rates and temperatures relevant for cutting. In [8], equations (1) - (4) were used to calculate a representative set of values for flow stress, strain, strain rate and temperature, respectively, directly from force measurement and assuming a geometry determined by the tool-shoe position. See specific definitions for the used terms in the Nomenclature.

This work represents a new step where the final objective is the generation of stress-strain curves that can be used in analytical models as well as using Finite Element Method (FEM) simulations. A new experimental setup for extrusion-cutting using discs as workpieces was developed and implemented on a CNC lathe, after which an experimental campaign was carried out to produce material data for pure copper using the extrusion-cutting method.

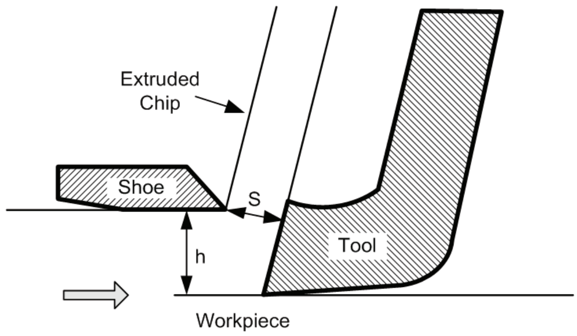

Figure 1 Extrusion-cutting produces a geometrically defined cutting process. Symbols refer to the Nomenclature [8].

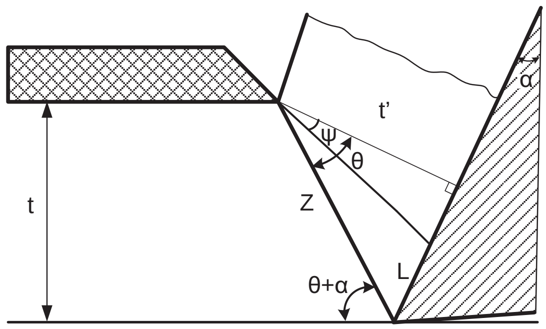

Figure 2 Upper-bound field for a shoe position near that for unrestricted cutting. Symbols refer to the Nomenclature [8].

$$\frac{p}{k} = \frac{\dot{W}}{kvhw} = \frac{\lambda}{cos\alpha} + \frac{2}{\lambda cos\alpha} - 3tan\alpha \qquad (1)$$

$$\gamma = \frac{\lambda}{cos\alpha} + \frac{1}{\lambda cos\alpha} - 2tan\alpha \qquad (2)$$

$$\dot{\gamma} = \frac{\gamma v sin(\alpha + \theta)}{d} \qquad (3)$$

$$\Delta T = \frac{k(\dot{W}/_{kvhw})}{J\rho c} \qquad (4)$$

2. Extrusion-cutting tests and generation of material data for copper

Fig. 3 shows the experimental setup for extrusion-cutting on a disk that was used for the campaign. The machine is a Mazak Nexus 200-II M CNC turning centre. A Kistler 9129 AA piezoelectric dynamometer was installed on the lathe turret for cutting force measurement in x, y, and z direction, referring to radial, tangential, and axial direction, respectively. A multi-channel charge amplifier 5070A was used in the measuring system which also involves a National Instruments data acquisition card and acquisition software elaborated in LabView.

An 8mmx8mmx60mm tool made of ASP 60 (high alloyed powder metallurgical high speed steel) with rake angle of 20° and a clearance angle of 6° was used. The tool is clamped on a tool holder fixed to the dynamometer while the shoe, made of tungsten carbide, is fixed to a separate shoe holder which is firmly fastened to the dynamometer support plate. Using this set-up, forces on the tool only are measured, as it was achieved using a similar set-up in [8].

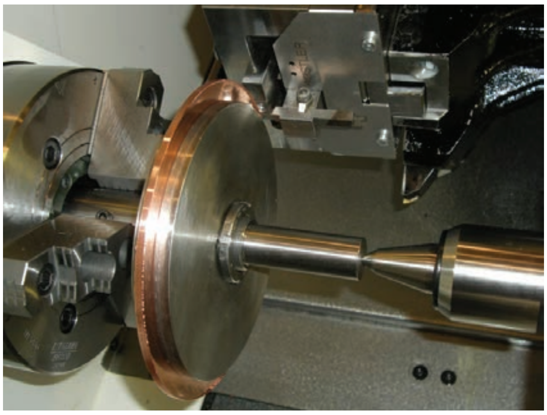

Figure 3 Experimental setup for extrusion-cutting on CNC lathe.

The workpieces were discs having an initial diameter of 210 mm obtained from 3 mm 95% pure copper half-hard sheet. The discs were mounted on a mandrel between two 10mm thick steel support disks, preventing workpiece deflection during the operation. The stiffness was further increased by the use of a tailstock. The tests were performed under dry conditions. Different tool-shoe gaps were examined adjusting S with thickness gauges while the tool offset with respect to the shoe h, which is nominally equal to the undeformed chip thickness *t* as well as to the radial feed, was maintained constant at 0.2 mm. As described in [9], to avoid vibrations and folding of the extruded chip as well as preventing material pile-up in the tool-shoe gap, the feed at the very start was set equal to 0.03 mm for 0.5 seconds and was then gradually increased to 0.2 mm. During the tests, the tool was inspected for wear and build up edge formation, the shoe was cleaned with abrasive paper, and the chips were collected.

A typical force profile recorded during the extrusion-cutting tests on copper is presented in Fig. 4. Considering the cutting force F_c, it is possible to detect three different zones. In the first region (A) forces are low, since a feed of 0.03mm was used at the very start of cutting. Then a second region (B) of approximately 3 seconds is visible, and here an average cutting force was evaluated for each test. Unfortunately, for all the different runs, it was not possible to define a plateau where the process can be considered stable. Moreover, due to considerable side spread of the material, it was necessary to correct forces for side spread calculating values corresponding to the same reference chip width of 3 mm. In the last region (C) the process was stopped.

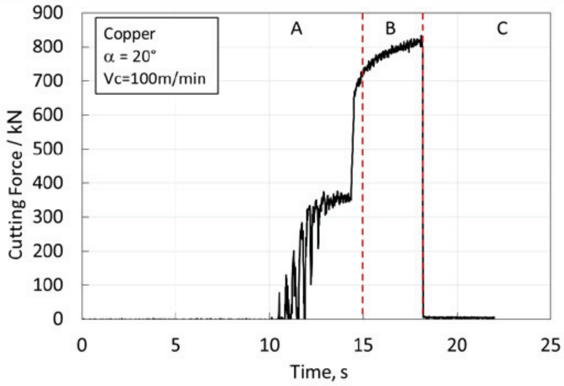

Figure 4 Main cutting force Fc in extrusion-cutting copper

The morphology of extruded chips was highly influenced by the tool-shoe gap, similarly to the findings in [9]. When the gap S is large, the chip back surface is not constrained by the shoe and ordinary cutting takes place. Since the conditions are those of normal cutting, a hard chip showing a lamellar structure on the back surface is produced. Decreasing the gap, chip extrusion partially takes place with a shiny surface in the middle of the chip and a rough morphology on the sides. The natural chip compression factor cutting copper under the given conditions is $\lambda = 5$. Fully extruded chips where the surface is shiny throughout the whole chip width were obtained in copper for a chip compression factor $\lambda = 3.5$. A further decrease of the gap led to vibration and folding due to a higher material resistance to being extruded. When the chip compression factor was around $\lambda = 1.4$, side cracks started being formed on the chip and wrinkles could be detected in its middle.

Several extrusion-cutting runs were performed with different tool-shoe gaps, maintaining constant the cutting speed and the feed. For each of them, the main cutting force acting on the tool was measured. For each test run, one point was defined representing a specific combination of shear flow stress, shear strain, shear strain rate and temperature, calculated using equations (1), (2), (3), and (4), respectively. To convert shear flow stress to effective flow stress, the Von Mises plastic flow criterion is used. Table 1 shows the calculated values of chip compression factor, equivalent strain, equivalent strain rate, temperature and equivalent stress.

Table 1 Experimental extrusion-cutting data for copper

Point no.	λ	ε	$\dot{\varepsilon}/s^{-1}$	T/°C	σ/MPa
1	1.50	0.91	18495	291	833
2	1.54	0.92	18852	285	813
3	1.58	0.94	19373	273	773
4	1.62	0.95	19790	270	760
5	1.68	0.98	20711	268	746
6	1.68	0.98	20637	299	840
7	1.71	0.99	21139	290	808
8	1.74	1.00	21538	257	706
9	1.75	1.01	21786	267	734
10	1.85	1.05	23715	270	730
11	2.25	1.24	37270	281	685
12	2.37	1.29	44622	261	612
13	2.47	1.34	54272	268	613
14	3.39	1.84	-	319	562
15	3.45	1.88	-	315	545
16	4.26	2.34	-	377	535
17	4.37	2.41	-	344	474
18	4.45	2.45	-	422	576
19	4.75	2.63	-	380	483
20	5.39	3.01	-	403	449

The calculations were carried out for 20 experimental points, covering the range of chip compression factors from pure extrusion-cutting until normal cutting. Strain-rate values for chip compression values above λ = 2.5 cannot be calculated because Eq. (3) becomes invalid when the deformation field, under the geometrical conditions determined by the chip compression and the tool rake angle, collapses to a single discontinuity corresponding to the shear plane in unrestricted cutting. To convert shear flow stress to effective flow stress, the Von Mises plastic flow criterion is used: $\sigma = k \cdot \sqrt{3}$. The following values were used for cutting temperature calculations:

- Room temperature: 20°C;
- c = 0.091 kcal/kg°C [10];
- ρ = 8.96 g/cm^3 [10].

Figs. 5-9 show all the calculated data from extrusion-cutting copper as functions of the chip compression factor. Fig. 5 shows the effect of the chip compression factor upon the extrusion pressure. It is possible to observe that the curve presents a point of minimum extrusion pressure p_{min} = 767 MPa for λ = 1.84, similarly to what was found in [8] and [11] for the case of brass, though with the point of minimum extrusion pressure at λ = 1.4.

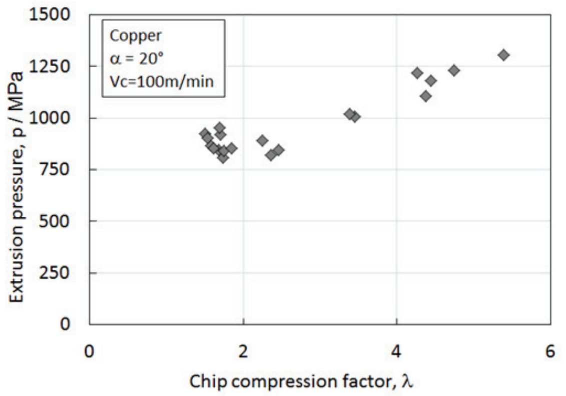

Figure 5 Cutting pressure on the cutting tool as function of chip compression factor.

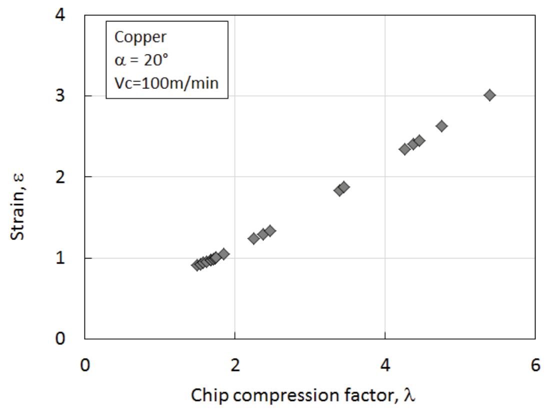

Figure 6 Equivalent strain as function of chip compression factor.

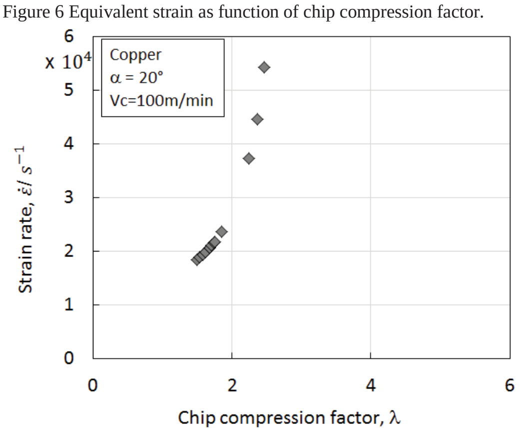

Figure 7 Equivalent strain-rate as function of chip compression factor.

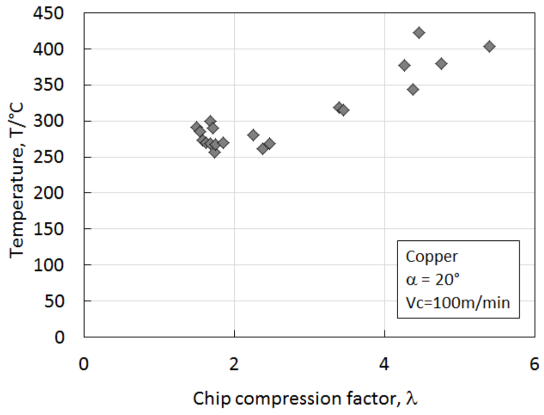

Figure 8 Cutting temperature as function of chip compression factor.

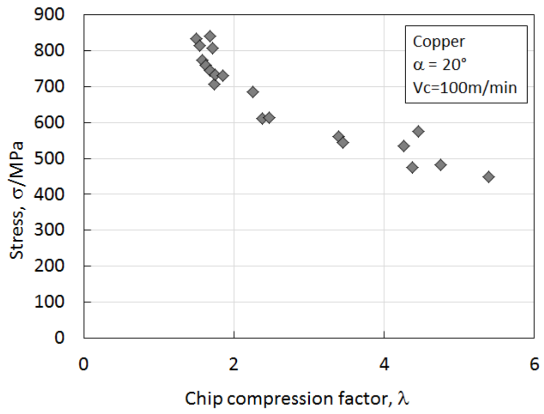

Figure 9 Equivalent stress as function of chip compression factor.

Fig. 6 shows the effect of the chip compression factor upon the equivalent strain. The curve presents no point of minimum strain because a chip compression factor around $\lambda = 1$ could not be achieved in copper.

Fig. 7 shows the calculated equivalent strain-rate as function of the chip compression factor. Values could only be calculated for chip compressions within the range of full extrusion while Eq. (3) becomes invalid for values in the neighbourhood of unrestricted cutting. The calculated strain-rate decreases when the chip compression factor decreases, keeping a general level of 20.000-40.000 s^{-1}.

Fig. 8 shows the calculated temperature as function of the chip compression factor. The shape of the curve is similar to that for the extrusion pressure, showing a minimum at $\lambda = 1.84$.

Fig. 9 shows the calculated equivalent stress as function of the chip compression factor. The stress is seen to increase in the entire extrusion-cutting area.

The value of the flow stress obtained by conventional testing of half-hard copper at low strain-rates is about $\sigma = 333$ MPa [10], corresponding to a shear stress of $k = 190$ MPa. It can therefore be generally concluded that the values obtained using the extrusion-cutting test, characterised by concurrently high values of strain, strain-rate and temperature, are higher than the values obtained with conventional tensile and compressive testing at low strains, strain-rates and temperatures, similarly to what was found in [8] and[11] for the case of brass.

A first conclusion from comparing Figs. 6-9 is that the simultaneous effect of strain, strain-rate and temperature on stress unclear, in that the flow stress on Fig. 9 increases for decreasing values of the chip compression factor, which could only be explained with a dominating effect from temperature, which is at its lowest but keeps a constant level on Fig. 8. The conclusion must be that the method needs to be further analysed and then validated using other work materials. There are several weak points in the approach, which definitely needs further development: (a) the slip-line and upper-bound methods are strictly valid for a perfectly plastic material behaviour, while strain hardening, strain-rate hardening and thermal softening are expected for metals such as copper; (b) Eq. (1) - (3) are derived using a simple upper-bound model consisting of a single discontinuity Z on the shear plane and a discontinuity L on the contact between tool and chip: this field can only be assumed for values of the chip compression factor in the neighbourhood of unrestricted cutting while a more complex deformation field should be used to cover the extrusion range; (c) Eq. (3) is derived for pure adiabatic temperature increase, disregarding friction heat from the shoe. On the other hand, the method seems promising in that extrusion-cutting is the only cutting process where the geometry needs not be determined experimentally, e.g., using quick-stop devices, chip thickness measurements, etc. Probably, a FEM analysis of the process would produce answers to some of the doubts that currently exist.

A further step in the analysis would be the definition of a 4D hyper-curve interpolating the different points obtained by the extrusion cutting analysis. From this hyper-curve, it is possible to extrapolate continuous 2D stress-strain at different temperatures and strain rates obtaining a more detailed description of the material properties under conditions relevant for cutting. This approach was undertaken in [11] for the case of brass, and it was also tried here. Following the method described in [11], one point for each set of data can be defined representing a specific combination of shear flow stress, shear strain, shear strain rate and temperature, calculated using equations (1), (2), (3), and (4), respectively. Unfortunately, it has not been likewise successful to proceed with the calculations using the data from copper; indeed, strange outliers occur even though the experimental data shown in Fig. 5-9 look reasonably consistent. At the time of writing, no evident solution seems to be available, and the issue is been object of further study.

3. Conclusions

A way of using extrusion-cutting as a technique for testing material under severe conditions of strains, strain rates and temperatures, has been implemented and used for cutting pure copper. Flow stress values for copper under machining-relevant conditions were obtained from measurement of the extrusion-cutting force on the tool and application of a simple upper-bound model for the extrusion-cutting process. The analysis has led to an estimation of the material flow stress at large strain, high strain rate and high temperature. It has been found that the flow stress under machining conditions is higher than that acquired with conventional testing. An attempt to extend the validity of test data to cover a range of cutting conditions was made, and suggestions for improvement of the simple theoretical model given. The work is currently continued toward a more complete description of material data with generation of a constitutive equation for use with FEM simulation.

4. Acknowledgements

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