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Towards cutting force evaluation without cutting tests

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ABSTRACT

Mechanistic cutting force modelling generally involves coefficients identification from machining tests. In order to develop multi-material cutting force models avoiding identification, several studies have tried to link cutting forces to mechanical properties from databases, whose relevance remains questionable. In this study, the cutting coefficients obtained by inverse identification from turning tests are compared with properties obtained from several mechanical tests. The correlations show that cutting forces can be estimated, without cutting tests, using hat-shaped shear tests. The originality of the approach is the behaviour proximity of the five machined materials used: thermal and mechanical treated pure coppers, brass and bronze.

1. Introduction

In 1998, a CIRP keynote paper [1] reported that most of the manufacturers preferred to use machining databases, instead of predictive models, due to the large variety of machining operations. Nowadays, cutting force estimation still requires experimental data obtained by instrumented cutting tests, generally using expensive multi-components dynamometers. In most of cases, cutting experiments are considered to be unavoidable if the machined material is changed.

Nevertheless, since the beginning of cutting modelling activities, many researchers tried to correlate cutting forces with mechanical characteristics of the work material. Among the first, in 1950, Lapsley et al. [2] tried to use tensile data, but the analysis was done only for one material. Later, Hastings et al. [3] compared cutting forces with high-speed compression test data from the literature, and also for a single material. In 1985, Armarego and Whitfield [4] mentioned that many researchers tried without success to eliminate cutting experiments from cutting force prediction, slowing down research efforts in this way. Notwithstanding, tensile tests and high-speed compression tests are still used nowadays in metal cutting studies, either to evaluate the machinability [5] or to characterise the mechanical behaviour of the work material for machining simulations [6]. Recently, a study tried to correlate specific cutting forces and tensile properties, both from the literature, using an empirical approach [7].

In the present article, the conclusions are established on an energy approach and a comparison with hat-shaped shear tests, seeing that the energy spent in the primary shear zone has been estimated to be up to 67% of the total by Astakhov and Xiao [8].

Hat-shaped specimens have been proposed by Hartmann et al. in 1981 [9] (as reported in [10]) to study shear loads. Even if hat-shaped experiments are more representative of the cutting process, Changeux [11] noted that there are some differences considering the hydrostatic stress, the shear strain rate – even in high-speed experiments –, and mostly the dimensions of the deformed volume introducing scaling and thermal effects. Despite these differences, these tests are quite simple and were widely used for the last twenty years to characterise the behaviour of work materials, especially for metal cutting simulations [12,13]. At a macroscopic scale, Hofmann and El-Magd [14] observed that the deformation work (or strain energy) per unit volume and the shear strain at fracture obtained by hat-shaped tests can be correlated with the chip breakability of the machined material.

In this study, five copper-based alloys, presented in Section 2, are used to clarify whether it could be possible or not to predict cutting forces from mechanical testing. For this purpose, the cutting coefficients obtained by inverse identification, as explained in Section 3, are compared with the mechanical properties obtained by tensile and hat-shaped experiments presented in Section 4. In particular, the comparison is based on an energy approach, whose results are detailed in Section 5.

2. Experimental approach and work materials

The originality of the proposed approach lies in the use of several materials which can be machined in the same conditions with reduced tool wear and with some behaviour similarities.

Initially, three pure coppers (Cu-OFE) have been studied under different metallurgical and mechanical states [15]:

- The first one corresponds to a standard cold-rolled copper (denoted Cu-Standard in this article), which is already work hardened.
- The second one (denoted Cu-Annealed) has been annealed by a heat treatment at 450 °C during 2 h.
- The last one was strengthened by using equal channel angular extrusion process (denoted Cu-ECAE).

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These three work materials are expected to have exactly the same elastic and thermal properties, being the closest machined materials conceivable. Later, the results have been completed by adding two standard copper alloys: a bronze (CuSn12) and a brass (CuZn39Pb2), and also by evaluating the repeatability of the measurements, as exposed in this article.

The dimensions of all the blanks were imposed by the ECAE tools, which allows 35 mm diameters cylindrical samples to be treated (Fig. 1(a)), and used afterwards to manufacture the testing specimens.

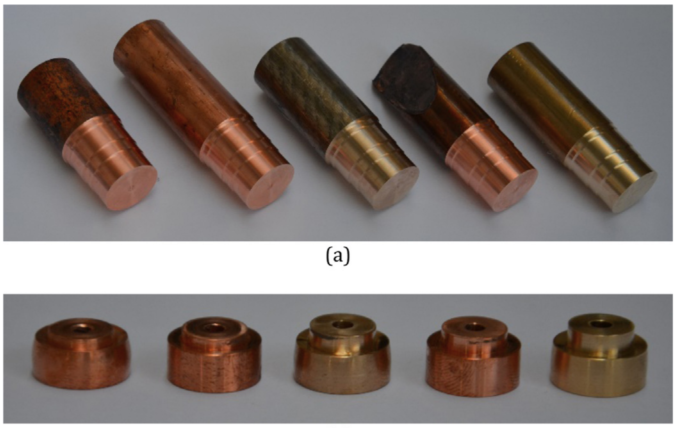

Fig. 1. The five tested materials: (a) machined samples (ϕ 35 mm); (b) hat-shaped specimens (ϕ 14 mm) after compression.

3. Analysis from cutting tests

3.1. Experimental set-up and set of experiments

Due to the small diameter of the samples, it was not possible to perform orthogonal cutting tests in turning configurations (disk or tube). Therefore, only longitudinal turning tests have been conducted using a single round carbide insert (Sandvik RCGX1204M0-ALH10) for all the tests, whose cutting edge radius r_n has been estimated to be about 17 ± 2 μm.

The turning tests have been performed on a 2-axis lathe (Somab, model Transmab 400) with flood lubrication. Cutting forces have been measured using a Kistler 9121 dynamometer together with a Kistler 5019 charge amplifier. Signals have been digitised by a NI PCI-6221 data acquisition card and treated in DasyLab software.

For each machined material, a set of five turning tests has been repeated three times, paying attention that there has been no interaction between tool wear and machined material. The five couples of cutting parameters (f, a_p) are represented in Fig. 2 and correspond to finishing conditions as shown by the h_{max} iso-lines.

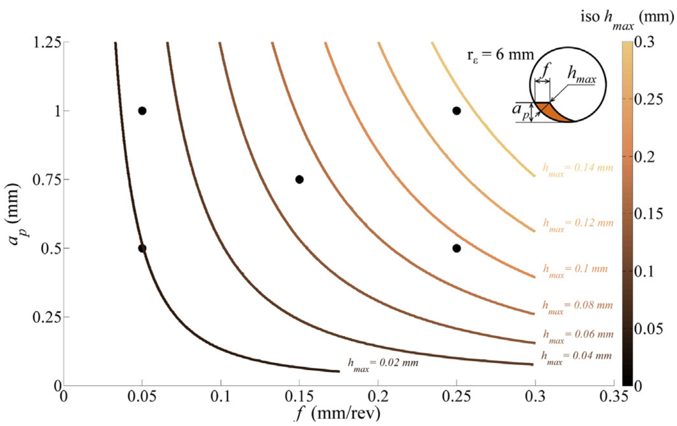

Fig. 2. Set of five cutting experiments, at constant V_c = 250 m/min.

3.2. Inverse identification of the local cutting force model

The cutting forces are modelled using the edge discretisation principle, graphically represented in Fig. 3: the global cutting force component F_c is calculated by summing up the contribution of the local cutting forces f_v (parallel to V_c) applied along the cutting edge, as expressed in Eq. (1).

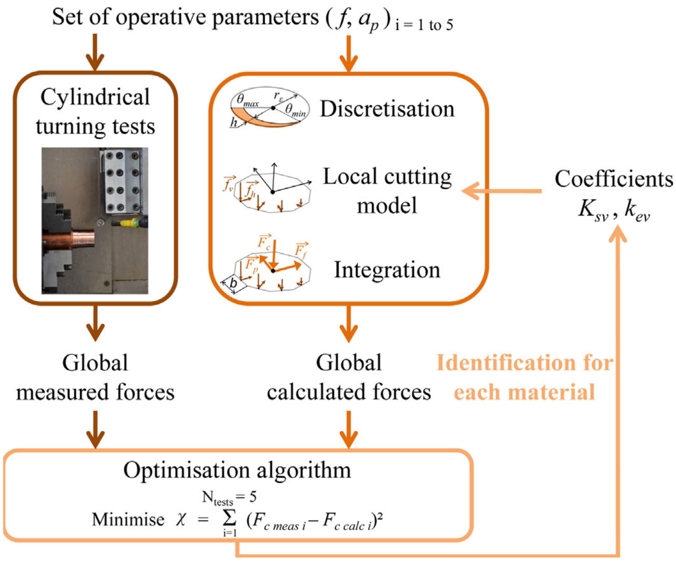

Fig. 3. Principle of the inverse identification.

The local forces are expressed as a linear function of the uncut chip thickness h, as shown by Eq. (2), using two cutting coefficients K_{sv} and k_{ev}. The first term is assumed to be linked to the shearing process, while the second should represent the edge effect (also called ploughing effect) [4].

$$F_{c\,calc} = \int_{\theta_{\min}}^{\theta_{\max}} f_v(\theta) \cdot r_\epsilon d\theta \tag{1}$$

$$f_v(h) = K_{sv} \cdot h(\theta) + k_{ev} \tag{2}$$

The principle of the discretisation methodology together with the uncut chip thickness calculation as a function of θ are detailed in Ref. [16].

The two coefficients (K_{sv} and k_{ev}) have been determined by inverse identification, as graphically explained in Fig. 3, by comparing modelled and measured global forces consisting in minimising the objective function χ as expressed by Eq. (3). This identification has been done three times for each work material from each set of force measurements.

$$\chi = \sum_{i=1}^{5} (F_{c\,meas\,i} - F_{c\,calc\,i})^2 \tag{3}$$

The averages of the three identified values for each material are given in Table 1 together with the standard deviations. It should be noted that the specific cutting force K_c can be calculated as a function of h from Eq. (2) by dividing f_v by h. The chosen cutting model is thus able to return the so-called "size effect" [17] for each material.

The aim of the mechanical tests presented in Section 4 is to determine the possibility of finding mechanical data which can be

Table 1
Identified coefficients of the mechanistic model for the five machined materials.

Material	K_{sv} (N/mm^2)	k_{ev} (N/mm)
Cu-Annealed	1416 ± 74	21.5 ± 1.5
Cu-Standard	1369 ± 95	20.2 ± 3.3
Cu-ECAE	923 ± 121	15.8 ± 1.9
Bronze	884 ± 92	11.5 ± 2.7
Brass	675 ± 13	6.5 ± 0.21