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A treatise on material characterization in the metal cutting process. Part 1: A novel approach and experimental verification

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Abstract

Everyday practice of cutting process planning requires reliable cutting force estimates, which currently can be obtained only from process-dependent machinability databases. The greatest obstacle to develop a more basic, efficient approach is a lack of understanding of material behavior under unique deformation conditions of cutting. Since metal cutting involves the physical separation of the chip from the rest of the workpiece, this paper defines the metal cutting process as the purposeful fracture of workpiece material. Part one of this two-part paper presents a novel approach of characterizing the resistance of workpiece material to cutting. It is shown that the strain at fracture is the most general material behavior characteristic. The experimental results show that the strain at fracture measured in incremental compression is consistent with that measured in orthogonal cutting when all deformation variables are properly accounted for and that, contrary to the results obtained using other kinds of material characteristics, the resistance to cutting of workpiece material in orthogonal cutting is not affected by high strains, strain rates and temperatures occurring in the cutting process. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Metal cutting process; Novel approach; Fracture; Experimental verification

1. Introduction

Over the last hundred years an extensive study has been carried out on the machining of metals. Most of this focused on the down-to-earth reduction of machining costs and a pragmatic approach to the manufacture of parts of acceptable dimensional accuracy and surface quality. Unfortunately, a much smaller volume of research has been devoted to discover the fundamental mechanisms underlying the metal machining processes in general, as opposed to seeking case solutions for particular machining problems. The real boom in fundamental metal cutting research, in 1960s, has brought the field both the recognition of the need for an applicable metal cutting theory as well as the reputation of being extremely complex. Since then, the practice has advanced by its own costly way of trial and error, whilst the fundamental research has experienced a decay after producing huge amounts of data that match the results of practice only occasionally.

The modern history of metal cutting began in 1945 when Merchant published his vision of the metal cutting phenomena [1]. As demonstrated by an excellent survey presented by the CIRP working group on chip control [2], numerous attempts to improve the theory proposed by Merchant failed to improve its predicting ability. Moreover, the original objectives of metal cutting research become somewhat obscure [3]. Instead of the original destination, which is to establish a predictive theory, the center of gravity has been shifted to develop theories of descriptive nature that only explain post-process phenomena, thus have a very limited prediction ability. As a result, no significant progress has been made, and after may years of study, theory is still lagging behind practice. Shaw in his book ([4], p. 200), which summarize his lifetime experience in the field, came to the discouraging conclusion that it is next to impossible to predict metal cutting performance.

Nevertheless, university courses on metal cutting and thus the corresponding textbooks (e.g., [5]) continue to teach Merchant's theory since it offers the simplest explanations for the metal cutting phenomena although no physical background is provided.

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Nowadays industry relies completely upon empirical data as these are presented by tool and machine tool manufacturers, as well as by professional engineering associations, through handbooks and seminars. Since these recommendations do not follow from a common theory behind them, they provide only a good "starting point" thus leaving the users, at their own cost, to determine the optimal values of cutting parameters for each particular case they may have, and for an outside observer with obscure knowledge in the field, it may appear that the industry is doing very well this way.

This two-part paper presents a novel approach to the characterization of workpiece material in cutting. It points out that the predictability of the cutting process depends entirely on the accuracy with which the properties of the workpiece material can be predicted in the cutting process. It establishes that the known approximation of the metal cutting process, referred to as the model for orthogonal cutting, cannot be used to predict metal cutting performance.

2. What has to be predicted according to the existent theories?

In the author's opinion, at the present stage of development, the predictability of a metal cutting theory depends entirely on the accuracy with which it accounts for the properties of the workpiece material, since the design and geometry of the cutting tool along with the properties of the tool material are well-known and the cutting regime can be set at any desirable level and/or can be varied according to any defined sequence. One may argue, however, that the mechanical properties of the workpiece material seem to be also well-known and tabulated in the corresponding reference books. Since the model for cutting is known [1], there should be no problem in the prediction of metal cutting performance. However, this is not the case [2].

The real problem here is in the definitions of the properties of workpiece materials. The known mechanical properties of the workpiece have been defined in the standard tensile, compression, etc., tests. Johnson and Mellor [6] begin their book with the following statement "the tensile test is easily and quickly performed but it is not possible to do much with its results, because one does not know what they really mean". In other words, it is not clear how to correlate the properties obtained in the standard tensile test, where a uniaxial state of stress is the case, with those involved in deforming processes, where triaxial states of stress complicated by high strains and strain rates are common.

The well-known Merchant's force model (Fig. 1) [1] is the only model basically accepted in practically all known publications on metal cutting [4,5,7,8]. The core of the model includes the determination of the shear plane component F_S of the resultant cutting force as follows:

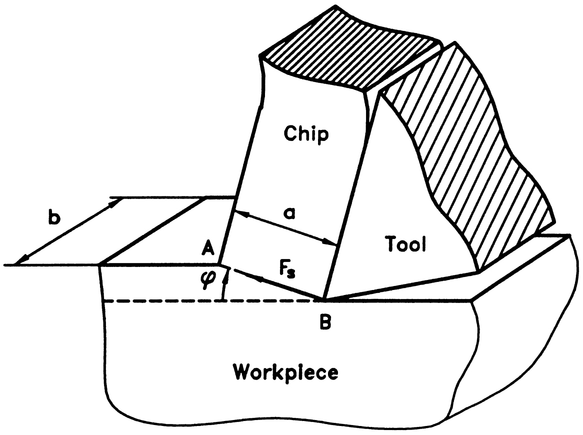

Fig. 1. Merchant's model for orthogonal cutting.

$$F_S = \tau \frac{ab}{\sin\varphi}, \tag{1}$$

where τ is the shear flow stress along the shear plane AB, a the uncut chip thickness, b the width of cut and φ is the shear angle.

Although many studies on metal cutting have attempted to derive theoretically or obtain experimentally, the flow shear stress, this is still one of the most controversial issues in the field, since the results obtained using Eq. (1) only occasionally match experimental results. There are several principal questions concerning the flow shear stress of workpiece material in cutting. Could the stress–strain relationships obtained in the standard tensile (compression) test be used in metal cutting? Would the stress in the deformation zone stop to grow or even start to decrease (an idealistic idea which stands behind so-called high-speed machining [9]) in the case of large strains as those in metal cutting? Is the flow shear stress affected by the high strain rates (10^4–10^8 greater than that in the standard tensile test) and high temperatures occurred in cutting? Practically all serious studies done on metal cutting contain the direct or indirect answers to these questions.

3. A review on the attempts to predict the flow shear stress

It is logical to assume that the theory of plasticity, known also as engineering plasticity, the main aim of which is to develop the mathematical techniques for the prediction of the plastic deformation of the workpiece in various circumstances, particular in a complex stress state, has been used in attempts to predict the flow shear stress in metal cutting. The application of the mathematical theory of plasticity to the problem of metal cutting originates from Hill [10]. Hill first hypothesized that the solution to the metal cutting process is not unique and that the steady-state mode of deformation would depend on the conditions encountered in the initial transient period of deformation. For an assumed class of solutions having a shear plane, when machining a rigid–perfectly plastic material with a sharp tool, Hill was able to determine a range of admissible shear angles. The limits on the range were imposed by the requirement that the metal should not be over-stressed at any point. Analyzing the hypotheses proposed by Merchant [1] that the shear plane in metal cutting would assume such an inclination as would ensure that the work performed in the cutting process would be a minimum, Hill came to the conclusion that since the geometry of deformation in machining is not known a priori, the principle of minimum work could not be applicable. Later on, in 1983, Rubenstein [11] presented the support of this conclusion. In the absence of a way to choose a particular solution uniquely from within the possible range, Hill conjectured that the actual mode of deformation would probably be dependant on the exact conditions during the initial stage of cutting. Dewhurst [12] has also argued strongly for such non-uniqueness of machining.

At this point it is worthwhile to discuss the application of the principle of minimum energy in metal cutting. On one hand, this is one of the fundamental principles of nature and thus should be applicable to the analysis of any real physical system. On the other hand, the application of this principle in metal cutting leads to conditions that cannot be fulfilled physically, thus being at odds with the theoretical, and this is much more serious, with the experimental results [11]. In the author's opinion this contradiction stems from the fact that the authors have analyzed an under-determined hypothetical system known after Merchant [1] as the model for orthogonal cutting. It is surprising that the researches have questioned the applicability of the basic principle rather than re-considering the known physical model. If the non-uniqueness of machining is the case, the search for predictive models of machining could prove to be futile.

The main ideas proposed by Hill had a great influence on the further works on the theoretical modeling of the metal cutting process. There have been a number of attempts to develop models that can predict the resistance of the workpiece material to cutting as a first step towards the prediction of cutting forces, tool wear, quality of the machined surface, etc. These models are now to be considered briefly.

Three major approaches to the determination of the thermomechanical behavior of metals in cutting may be distinguished, although all the three have in their base the same or a similar model of the cutting process as proposed by Merchant [1] so that they consider the flow shear stress on the shear plane as the main property of workpiece material in cutting.

3.1. *The first approach*

This approach originates from Merchant himself [1] and is based on the assumption that the flow shear stress on the shear plane is equal to that obtained from the standard tensile test [3,7,13–15]. Therefore, the stress–strain curves obtained in the standard tensile test can be used in metal cutting.

It is worthwhile to discuss here the results of two works: by Zorev [7] and by Von Turkovich [16].

Zorev has conducted a great number of cutting experiments to establish the flow shear stress. In the experiments, he used a number of workpiece materials, cutting tools and cutting conditions. The essence of his work is the comparison of the resistance to plastic deformation during cutting and during mechanical testing, particularly during tension and compression. For the range of deformation studied in tension, the relationship of the maximum shear stress (τ) (which is wrongly termed in the book as the tangential stress due to poor translation) to the true shear strain (ε_t) was represented in the form of the following equation:

$$\tau = A\varepsilon_t^m. \tag{2}$$

In double logarithmic coordinates ($\log \varepsilon_t - \log \tau$), Eq. (2) is represented as a straight line. By continuing such lines into the range of large plastic deformations, appropriate to the cutting process, it is possible to compare the values of the shear stresses during cutting (τ_{sp}) with the extrapolated values of the maximum shear stress during tension (τ). The comparison made using a number of experimental data for a great number of different workpiece materials, cutting regimes and tool geometries shows that the extrapolation of the relationship defined by Eq. (2) to a deformation of ε_t=2 to 3 produces approximately the same values of the maximum shear stress during tension (τ) as for the shear stresses during cutting (τ_{sp}). It is therefore possible to determine approximately τ_{sp} from the results of tensile tests by using the following equation:

$$\tau_{sp} = A2.5^m. \tag{3}$$

Studying the influence of the temperature on the shear stress in cutting, Zorev concluded that at high cutting speeds, the temperature has comparatively little influence on this stress. Moreover, the experimental results obtained suggest that the assumption that the thermal strain-hardening of steels as the temperature in the chip formation zone rises to the blue shortness temperature leads to the reduction of the deformation and the chip compression ratio, has no grounds.

Von Turkovich compared the shear stress computed by means of equation due to Merchant with that calculated by means of the universal equation, which expresses the shear stress as a function of dislocation density in the following form:

$$\tau = A_1 G b_r \sqrt{\rho}. \tag{4}$$

Here, A_1 is a constant of order of *1*, G the shear modulus, b_r the Burgers vector magnitude and ρ is the dislocation density.

The comparison, made assumed that the process of deformation in metal cutting takes place at constant dislocation density, showed a fairly good agreement of the results for iron and copper when the value of the shear modulus in Eq. (4) was selected according to the cutting temperature.

Before proceeding further, it would be appropriate here to note that the authors of the works of this group had tried to reveal the influence of cutting temperature, high strain and strain rate on the flow shear stress: however, no such influence was found.

3.2. The second approach

According to the second approach, the flow shear stress in cutting appears to be much higher than that obtained in the standard material test. This is explained by the flow shear stress obtained in the standard tensile test being modified by high strain, strain rate, and/or their linear/non-linear combination [4,17–20]. According to this approach, the stress–strain relationships obtained in the standard tensile test cannot be used in metal cutting. Instead, a number of new stress–strain relationships, mostly taken from the work on material properties under high strain rate conditions, have been proposed. As before, these studies also provide numerous theoretical and experimental results to support their conclusions.

It is worthwhile to discuss here the work done by Oxley [18]. Analyzing the results of the experimental studies of Kececioglu [21] and Nakayama [22] conducted at relatively high cutting speeds and of Palmer and Oxley [23] conducted at low cutting speeds and using the known velocity diagram, Oxley concluded that for practical cutting speeds, which are typical, say, for turning, the average shear strain rate in the shear zone lies in the range from 10^3 to 10^5 s^{-1} or even higher. These values are much higher than the strain rates of 10^{-3} to 10^{-1} s^{-1} normally incorporated in conventional tension and compression tests. Since it is known that the rate of strain has a marked effect on a material strain–stress properties in the standard material tests, Oxley assumed that, in order to be realistic, any machining theory should take account of strain rate effects. The temperatures generated in machining and their effect on flow stress would be expected to be equally important but this was not fully recognized in Oxley's study.

3.3. The third approach

The essence of the third approach is the consideration of the combined influence of strain-hardening and thermal-softening effects on the flow shear stress. As before, a number of new stress–strain relationships have been proposed [9,24–28]. Also, numerous theoretical and experimental proofs have been provided to support this point.

It is worthwhile to discuss the conclusion made by Spaans [24]. Spaans, acknowledging the influence of the temperature, strain and strain rate on the flow shear stress, has concluded that the effect of the temperature is balanced by a strain rate effect in such a way that the flow shear stress remains equal to that in the standard tensile test.

The foregoing brief review of previous works reveals a broad scatter in the descriptions of the thermomechanical behavior of metals in cutting. The important issue here is that the authors representing the second and third approach have never acknowledged (mentioned, disproved, discussed, etc.) the work of the authors representing the first approach who had studied the influence of high strain rates and temperatures on the thermomechanical behavior of materials in cutting but did not find it significant. Furthermore Shaw [4], analyzing the flow shear stress in cutting, has concluded that this stress cannot be predicted in terms of properties derived from ordinary material tests, and therefore, it is next to impossible to predict metal cutting performance.

In the opinion of the writer, a reason for the discussed significant scatter in the reported results is in the consideration of the flow shear stress as a sufficient mechanical property characterizing the resistance of the workpiece material to cutting.

4. What has to be predicted in reality?

Machining is always considered as one of processes by which metals and alloys are formed and shaped, i.e., as one of the forming processes [29]. However, it seems that no one study points out that a principal difference exists between machining and all other metal forming processes. In machining, the physical separation of the layer to be removed (in the form of chips) from the rest of the workpiece must occur. To achieve this, the stress along the line which separates the layer to be removed from the remaining workpiece should exceed the ultimate stress of the workpiece material, whereas other forming processes are performed applying a stress which is sufficient to achieve the well-known flow shear stress in the deformation zone. The objective of machining is to separate the layer to be removed with minimum possible plastic deformation, and therefore, the energy spent on the plastic deformation in cutting may be considered as wasted. On the other hand, any metal deforming process, especially involved high strains (deep drawing, extrusion), uses plastic deformation to accomplish the process. Parts are formed into useful shapes such as tubes, rods, and sheets by displacing the metal from one location to another [30]. Therefore, a better material, from the viewpoint of metal forming, should exhibit a higher strain before fracture. It is understood that this is not the case for machining, where a better material should exhibit a strain at fracture that is as low as possible.

It follows from the foregoing consideration that amongst other important parameters characterizing the behavior of a material in cutting, toughness should be considered as having prime importance. The toughness of a material is defined as its ability to absorb energy in the plastic range.

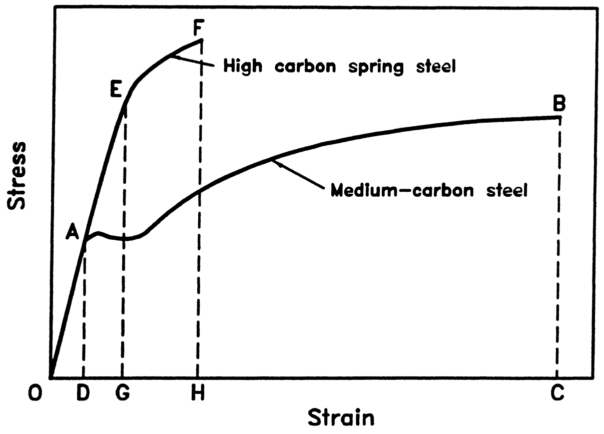

Fig. 2. Comparison of the stress–strain curves for high and medium carbon steels.

One way of looking at toughness is to consider it as the total area under the stress–strain curve [29]. This area is an indication of the amount of work per unit volume which must be done on the material to cause its fracture. Fig. 2 shows the strain–stress curves for high- and low-toughness materials. The high-carbon spring steel has a higher yield stress that makes its elastic energy necessary to reach a proportional limit (represented by triangle OEG in Fig. 2) that is much higher than that (represented by triangle OAD in Fig. 2) for the low-carbide structural steel. However, the low-carbon steel is more ductile and thus has a greater total elongation. The total area under the stress–strain curve for this steel (denoted as OABC in Fig. 2) is much greater than that for the high-carbon steel (OFH in Fig. 2), and therefore, the former is a tougher material. This illustrates that toughness is a parameter which comprises both strength and ductility.

Several mathematical approximations for the area under the stress–strain curve have been suggested. For ductile materials having stress–strain curves such as that shown in Fig. 2, it can be approximated by the following equation [29]:

$$U_{\mathrm{T}} = s_{\mathrm{u}}\varepsilon_{\mathrm{f}}. \tag{5}$$

The terms of Eq. (5) may be interpreted as follows: U_{T} is the amount of work per unit volume which must be done on the material to cause its fracture, s_{u} the ultimate stress of a material and ε_{f} is the fracture strain.

In terms of metal cutting, U_{T} may be thought of as the energy necessary to separate the layer to be removed from the rest of the workpiece.

Analyzing Eq. (5), it may be concluded that out of two parameters, that define the energy that is necessary to be spent to achieve fracture, only the fracture strain depends on the parameters of deformation, since the ultimate stress of a material may be considered as its mechanical constant (at least at temperatures of less than $0.6T_{\mathrm{m}}$, where T_{m} is the melting point of the material [29]).

From the viewpoint of metal cutting, therefore, the fracture strain may be considered as the most important characteristic of a ductile material since it defines the energy involved in the cutting process and thus all other process' parameters. Unfortunately, as discussed above, in metal cutting it is believed that the flow shear stress is the main parameter defining all other process' parameters and thus the main attention has been paid in the past studies to the determination of this stress theoretically or/and experimentally. However, the above discussion shows that the flow shear stress cannot be used to define the energy involved in the cutting process. However, the existent theories do not leave any room for other mechanical properties or parameters of the workpiece material to calculate the cutting process's parameters, for example the cutting force.

5. Experimental verification

To establish that the proposed approach is the case in the real metal cutting process, the deformation process in metal cutting should be compared with those in other deforming process at the point of fracture. This can be accomplished by comparing the energies spent in the cutting process with that spent in any other deformation process under similar strains at fracture. In the present study, the cutting process is compared with incremental compression, the latter being chosen for the comparison with cutting for two reasons. First, in incremental compression, the friction losses are negligibly small and all of the energy is spent in plastic deformation. Secondly, incremental compression is the only standard material test where strains as high as those in metal cutting may be obtained under controllable conditions (ASTM Standard Test Method F 1624-95).

Four steels were chosen for the comparison, which were numbered as follows: (1) plain carbon steel AISI 1040; (2) low-alloy steel AISI 3310H; (3) low-alloy steel AISI 4130; (4) austenitic stainless steel AISI 30400. This numbering will be retained throughout further discussion.

5.1. Incremental compression

A Computer-Controlled Material Testing System 647 (Concordia Center for Composites) was used for the experiments. Following the methodology proposed by Rosenberg and Rosenberg [31], for each chosen material the experimental relationship "axial stress σ-strain ϵ" under high strains was obtained experimentally. Fig. 3 shows the results for steels 1 and 4. As such, the following high fracture strains for the steels under study were achieved in the incremental compression tests: ϵ_1=7.2; ϵ_2=5.1; ϵ_3=4.4; ϵ_4=3.9. These were calculated using the known equation proposed by Zorev [7]:

$$\epsilon = 1.5\ln\frac{l_0}{l_1} \tag{6}$$

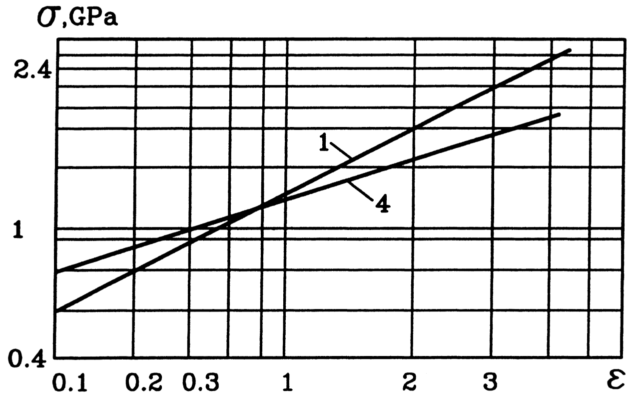

Fig. 3. The axial stress in compression vs. true strain for materials 1 and 4.

in which l_0 is the initial length of a specimen before load is applied; l_1 is the deformed length of the specimen.

Under the achieved high deformations, for all of the materials used in the study, the flow curves in the form of a power expression [7,29] $\sigma = K\epsilon^m$, where K and m are constants for a given material, were obtained.

As mentioned above, in incremental compression, the friction losses are negligibly small so that all of the energy is expended in plastic deformation. Hence, the expression for the incremental work done in compression would be:

$$\mathrm{d}W_{\mathrm{com}} = P\mathrm{d}l_i. \tag{7}$$

Here, P is the instantaneous compression force, which is defined as

$$P = \sigma A_{\mathrm{i}}. \tag{8}$$

Here, A_{i} is the instantaneous cross-sectional area of the specimen, $A_{\mathrm{i}} = V/l_{\mathrm{i}}$, l_{I} the instantaneous length of the specimen, and V is the volume of the specimen.

Substituting Eqs. (6) and (8) into Eq. (7), one may obtain:

$$\mathrm{d}W_{\mathrm{com}} = KV1.5^m\left(\ln\frac{l_0}{l}\right)^m\frac{\mathrm{d}l}{l}. \tag{9}$$

The total work per unit volume done in compression is obtained by integrating Eq. (9) in the limits from the initial length l_0 to the final length l_1 as

$$W_{\mathrm{com}} = \frac{K\epsilon^{m-1}}{1.5(m+1)}. \tag{10}$$

Using this equation and the experimentally obtained values of K and m, the total work per unit volume done in compression W_{com} as a function of the true strain ϵ calculated using Eq. (6) is shown in Fig. 4 with solid lines for each (1–4) material used in the experiments.

5.2. Metal cutting

The total work per unit volume (specific work) done in cutting may be defined as follows [4,7]:

$$W_{\mathrm{cut}} = \tau\epsilon_u. \tag{11}$$

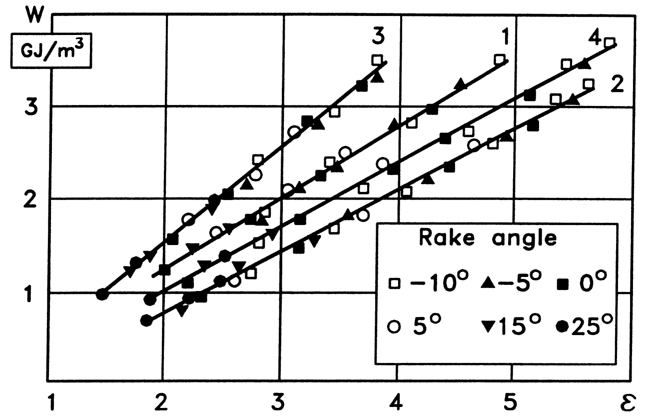

Fig. 4. Comparison of the specific work done in compression with that in cutting. The results obtained in incremental compression are shown by solid lines and those in metal cutting are shown by symbols.

Here, τ is the shear stress at fracture and ϵ_{u} is the final true shear strain.

Two important conclusions follow from Eq. (11). First, the specific work done in cutting depends only on the fracture true shear strain because the shear stress at fracture of the strain-hardened workpiece material depends also on this strain. Second, if the high temperature and strain rate occurred in cutting will affect τ then they must affect W_{cut}.

To obtain the total work per unit volume done in cutting, cutting experiments were carried out. They included the determination of the cutting force, the chip compression ratio and the shear strain. The experimental set-up used is discussed in the Appendix A. For the comparison, the results of the cutting experiment are plotted with the corresponding symbols in the same figure (Fig. 4) where the results of the incremental compression test are shown with solid lines.

The comparison of the incremental compression test results (solid lines in Fig. 4) with those obtained in the cutting tests (symbols in Fig. 4) shows that, regardless of the cutting regime, including the feed, cutting speed, tool material, tool geometry, as well as the type of cutting fluid used, the specific work done in cutting is the same as that done in incremental compression. This confirms the validity of the proposed approach. Further, another interesting fundamental result has been obtained, namely, that neither the temperature nor the strain rate affect the resistance of the workpiece material in cutting, because the incremental compression was conducted at room temperature with a very small strain rate whereas the strain rates in cutting were much higher and the temperature in the deformation zone reached 300–500°C.

5.3. Influence of high temperatures

Now consider the effect of high temperatures in the machining zone on the flow shear stress of the workpiece material.

It is known [29] that the stress–strain curve and the flow and fracture properties derived from the tension test depend strongly on the temperature at which the test is conducted. In general, the strength decreases and ductility increases as the test temperature is increased. This property is used widely in hot-rolling, drawing and other bulk deformation processes to reduce the energy consumption and to increase the workability of the workpiece materials [29]. The same idea stands behind machining with workpiece pre-heating, where the workpiece is pre-heated by an external heat source, for instance by a plasma arc [28,30]. Therefore, it seems to be quite logical to assume that the high temperatures occurring in cutting may reduce the shear stress at fracture of the workpiece material.

To study the influence of temperature on the properties of the workpiece material in metal cutting, the cutting process is assumed to be adiabatic [4,7]. This assumption has firm grounds as far as orthogonal cutting is concerned, since at the high speeds used in cutting, the transfer of heat in the direction of motion occurs mainly by transportation and the conduction term can be neglected. This means that the heat generated in the deformation zone and the average temperature θ_s in this zone are proportional to the specific work of metal removal W_{cut} being done in shearing. As such, the average temperature can be calculated as [7]:

$$\theta_s = \frac{W_{cut}}{J\rho c_p} + \theta_0, \tag{12}$$

where J is the mechanical equivalent of heat, ρ the density of the workpiece material, c_p the average specific heat and θ_0 is the temperature prior to deformation.

It has been shown that the specific work in metal cutting W_{cut} may reach 3 GJ/m^3 or even more [7]. Thus, the temperature θ_s in the deformation zone may reach 300–500°C. It is known that the stress–strain curve for a given material assumes lower and lower values as the temperature increases, thus, at such high temperature, the flow shear stress of the workpiece material should decrease, also [29]. This, along with Merchant's model for chip formation, constitutes a logical background for numerous thermomechanical models for the workpiece material discussed above. However, the results shown in Fig. 4 do not conform to this assumption. Therefore, it is of prime importance to understand why the influence of temperatures in metal cutting seems to be at odds with the results of studies on material testing.

It is true that the yield and ultimate strength of the workpiece material decrease with temperature. However, that can occur if and only if this material is kept at this temperature for a certain period of time [32]. Therefore, it is necessary to estimate the period of time necessary for a micro-volume of workpiece material to pass through the deformation zone.

It follows from the above discussion that a micro-volume of the layer being cut, passing the shear zone, changes its velocity from the cutting speed v to the chip velocity $v_1 = v/\zeta$, where ζ is the chip compression ratio. Thus, the average velocity of the micro-volume is $0.5v(1-\zeta)$. Therefore, the time necessary to pass a shear zone having a width of h would be

$$T = \frac{h}{0.5v(1+1/\zeta)}. \tag{13}$$

Since the width of the shear zone is $h=0.5a$ [24], where a is the uncut chip thickness, it is possible to estimate the time that is necessary for a micro-volume to pass through the deformation zone for a typical cutting regime. When the workpiece is made of a plain carbon steel, a typical cutting regime is as follows: $v=120$ m/min$=2$ m/s; $\zeta=2.5$; $a=0.2$ mm. Thus, the estimated time is $T=0.000071$ s. With a workpiece made of a high-strength, low-alloy steel, the typical cutting regime may be as follows: $v=120$ m/min$=2$ m/s; $\zeta=1.3$; $a=0.05$ mm. As such, $T=0.000014$ s. As seen, the time necessary for a micro-volume to pass through the deformation zone is extremely short. As a result, there can be no temperature influence on the mechanical properties of the micro-volume of workpiece material.

In addition to a very short heating time, there are two other strong reasons why the temperature in orthogonal cutting plays no role in changing the flow shear stress of the workpiece material. These two have never been considered in any study on metal cutting. They are:

1. It is well-known that the structural transformation temperatures in metals increase dramatically with the heating rate [24]. In metal cutting, the heating rate reaches hundreds of thousands or even millions of degrees per second, which significantly increases the structural transformation temperatures of the workpiece material.
2. Heat generation in the deformation zone follows the plastic deformation in this zone. Owing to the cutting speeds practically used being much higher than that of heat conduction, the micro-volume entering the deformation zone is not yet heated, and thus does not have an elevated temperature, heat being generated later as a result of the deformation of the micro-volume. Therefore, the micro-volume is heated over an even shorter time than that calculated in the examples.

Now the concept of mutual compensation in metal cutting may be revised. Spaans [24] suggested that, in metal cutting, an increase in the flow shear stress due to strain-hardening is compensated for by the corresponding decrease of this stress due to thermal-softening, so that the flow shear stress remains the same as in the standard material test. This suggestion becomes very convenient to explain a significant difference between the results obtained from the known theories of metal cutting and those obtained in practice, eventhough no experimental proof of this has been reported. The experimental data, presented in Fig. 4, opposes this

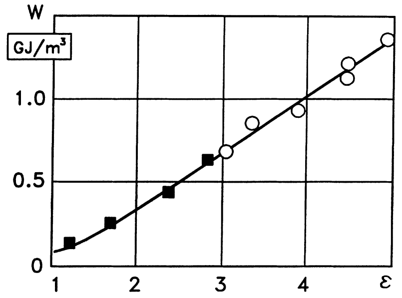

Fig. 5. The specific work done in compression (solid line) and in cutting ((■) low cutting speeds; (○) high cutting speeds) of a technical copper vs. true shear strain.

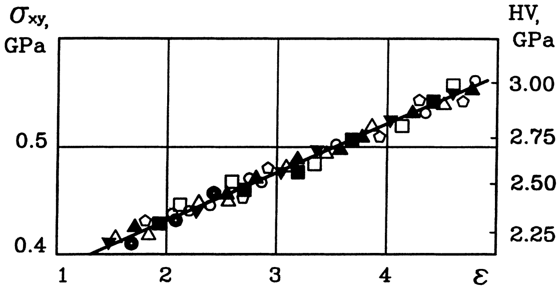

Fig. 6. Comparison of machining and incremental compression test results: the solid line represent results obtained in the compression test and the symbols represent the results of the cutting test. (s=0.29 mm/rev; rake angle (deg) (○) −20, (△) −10, (□) 0, (◆) 10; cutting speed (m/s) (▲) 0.66, (▼) 1.0, (■) 1.8, (•) 0.015).

suggestion. Moreover, to achieve an even greater difference in the conditions between cutting and compression, a technical copper was chosen as the workpiece material, as suggested by Rosenberg and Rosenberg [31]. Fig. 5 shows the results of the comparison between incremental compression and cutting. In the case of incremental compression (the solid line in Fig. 5) the strain rate was 10^{-3} s^{-1} (no heating). In cutting at very small cutting speeds ((■) in Fig. 5) this rate was 10^{-1}–10 s^{-1}, i.e. it is 100–100 000 fold higher (negligible heating). In cutting at high cutting speeds ((○) in Fig. 5) the strain rate was in the range of 10^{3}–10^{5} s^{-1} (high temperature). It can be seen that the relationships "strain–specific work" are identical eventhough the range of the experimental conditions is broad. Therefore, there are no grounds to believe that mutual compensation (or counterbalancing) of strain-hardening and thermal-softening is the case in metal cutting.

To finish the discussion, it is relevant to present the results of microhardness tests. It is known that the microhardness (HV) of the deformed material is uniquely related with the preceding deformation [33] and with the shear stress [31] gained by the specimen under consideration at the last stage of deformation. This makes it possible to obtain information about the extent and distribution of deformation and shear stress on the basis of microhardness measurements. By performing such measurement, the comparison of stresses and deformations in incremental compression with those in cutting can be made.

An incremental compression test was carried out using specimens made of steel 1010. For this test, the flow shear stress is related with microhardness as [31]:

$$\tau = 0.185\ \text{HV}; \quad 1 \leq \epsilon \leq 5. \tag{14}$$

The test result is shown in Fig. 6 by a solid line.

For the metal cutting test, steel 1010 was used. The samples of the deformation zone with the partially formed chip were obtained using a specially designed, computer-triggered quick-stop device. Using sequential hardness traverses, the strain and stress distributions in the deformation zone are obtained from the early stages of the workpiece material deformation to further advanced stages, when the chip is separated from the workpiece. The flow shear stress is defined as the maximum measured shear stress. The results for different tool geometry and tool feed are shown in Fig. 6 by corresponding symbols. The nearly perfect agreement between the results of the incremental compression test and the cutting experiment proves confirms again the proposed approach and that neither high temperatures nor high strain rates affect the resistance of the workpiece material to cutting in the case of orthogonal cutting.

5.4. The cause of a significant scatter in the reported results

Since Merchant introduced his model [1], it is a common belief that orthogonal cutting is a convenient model by means of which to study the mechanics of metal cutting. To conduct a study with this model, one should accept a number of assumptions well analyzed by Shaw [4]. The problem is that the results obtained with an orthogonal model are used to make some practical decisions in process or/and tool design featuring non-orthogonal conditions. Here, one practical example is given explaining a significant scatter in the experimental results obtained in studies of the thermomechanical behavior of workpiece materials.

It is known from the second law of thermodynamics that heat always flows spontaneously from a hotter to a colder body. Since the machining zone is a heat source, heat, leaving the machining zone forms around this zone a certain dynamic (time-dependant) temperature field. It is understood that for energy transfer by thermoconductivity, there is no priority direction, all the directions being identical. As might be expected, this heat expansion affects the workpiece material if and only if the velocity of the heat expansion is equal to or greater than the cutting speed with respect to the workpiece.

Normally, the cutting speeds encountered in practice employing modern tool materials are much higher than the velocity of heat expansion. Thus, in orthogonal cutting, there should not be any influence of the heat expansion on the workpiece material. However, there are two basically different reasons explaining why such influence was noticed and reported many times. They are:

1. The cutting speeds used in metal cutting studies with orthogonal models are usually much lower than those used in industry, especially when a quick-stop device is used [24]. Therefore, the velocity of heat expansion here may be less than, equal to or even exceeding the cutting speed, depending on the particular combination of the chosen cutting regime and involved materials' properties. It is clear that in the last two cases, the heat generated in cutting will affect the properties of the workpiece material.
2. Quite often, end tube turning is used to model orthogonal cutting [4,8,20,28]. In the author's opinion, such modeling causes a problem. Originally, in orthogonal cutting, the workpiece is assumed to be infinitely long and the cutting tool moves over it at the cutting speed. It is understood that if the cutting speed is greater than that of heat expansion, heat plays no role in orthogonal cutting. The velocity of heat expansion when the heat source also moves is characterized by the Peclet number:

   $$Pe = \frac{va}{w}. \tag{15}$$

   Here, v is the velocity of the heat source (the cutting speed) (m/s), a the uncut chip thickness (m), and w is the thermal diffusivity of the workpiece material, (m^2/s).

For $Pe>10$, the source moves faster than heat can expand, which is common for practical cutting conditions. It is important to emphasize here is that the tool never passes the same or even a neighboring point of the workpiece. In tube end turning, however, this is not the case. The cutting tool cames to the same point after each revolution. The residual heat from the previous revolution affects the flow shear stress at the current revolution and so on. This influence depends not only on the physical properties of the workpiece material and the cutter, but also on the chosen cutting regime, the dimensions of the workpiece, etc. All of these factors have not been accounted for in the known studies. To demonstrate a significant difference between orthogonal cutting and tube end turning, the Peclet number is calculated here for each of these processes under identical modeling cutting conditions, which were chosen to be as follows: workpiece material – steel 1040; thermal diffusivity of the workpiece material $w=6.67\times10^{-6}$ m^2/s; cutting speed $v=1.5$ m/s; uncut chip thickness $a=0.5\times10^{-3}$ m. For end tube turning, the additional conditions are: cutting feed $s=a=0.5$ mm/rev, the tube's mean diameter $d=0.1$ m. Using Eq. (15) one can calculate that for orthogonal cutting $Pe=112.4$ (since $Pe\gg10$, there is no influence of the residual heat); whilst for tube end turning $Pe=0.17$ (since $Pe\ll10$ there is a great influence of the residual heat). In addition to the residual heat, the residual stress unavoidably gained by the machined surface on the preceding pass may affect the flow shear stress on the current pass.

The foregoing analysis offers a reasonable explanation for the existence of many different models for the thermomechanical behavior of metals in cutting.

6. Conclusions

1. The main distinct feature of machining in comparison with other deforming processes is the physical separation of the layer to be removed (in the form of the chip) from the rest of the workpiece. To achieve this, the stress along the line that separates the layer to be removed from the remaining workpiece should exceed the ultimate stress of the workpiece material, whereas other forming processes are performed under a stress that is sufficient to achieve the well-known flow shear stress in the deformation zone.
2. The optimization of the machining process may be thought of as the minimization of the amount of plastic deformation with which the layer to be removed is separated from the rest of the workpiece. From the viewpoint of metal cutting, the fracture strain may be considered as the most important characteristic of a ductile material, since it defines the energy involved in the cutting process and thus all of the other process' parameters. Therefore, the prediction of machining depends entirely on the accuracy with which the strain at fracture can be predicted.
3. The significant strain and strain rate occurring in orthogonal cutting do not seem to affect the flow shear stress of the workpiece material and thus do not affect the workpiece material resistance to cutting.
4. Eventhough the temperature in the deformation zone is in the range of 300–500°C, this temperature does not seem to affect the flow shear stress of the workpiece material, and thus does not affect the workpiece material resistance to cutting under orthogonal cutting conditions. Therefore, orthogonal cutting should be considered as a cold-working process.

Appendix

Cutting test conditions

Since the cutting force is known to be very sensitive to even the smallest changes in the cutting process, special attention was paid to the selection of the conditions of the tests and to the experimental methodology. The test conditions were selected as follows:

(1) *Workpiece materials*: (1) plain carbon steel AISI 1040; (2) low-alloy steel AISI 3310H; (3) low-alloy steel AISI 4130; (4) austenitic stainless steel AISI 30400. The composition, the element limits and the de-oxidation practice had been chosen according to the requirements of standard ANSI/ASME B94.55M-1985 and were requested from the

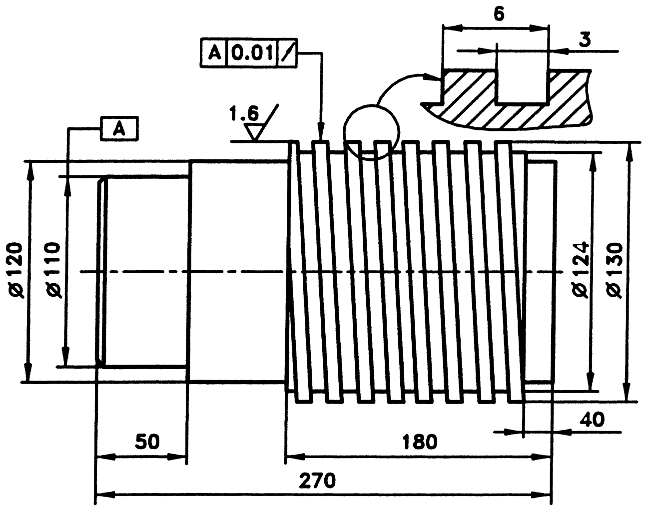

Fig. 7. Configuration of the workpieces used in the experiments (dimensions: mm).

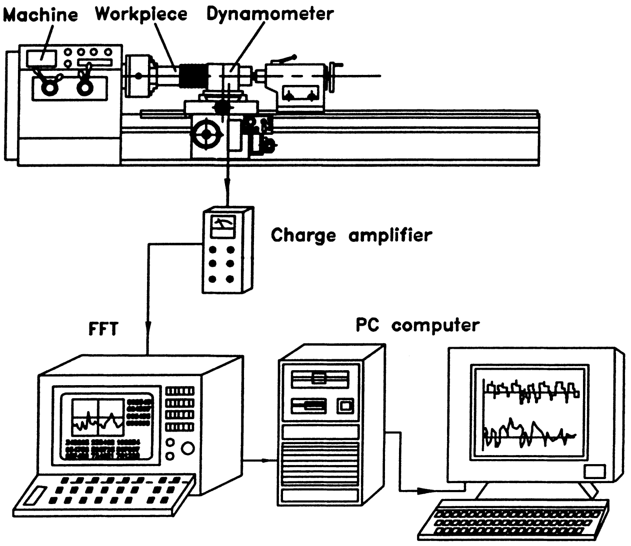

Fig. 8. Schematic diagram of the measuring set-up.

steel dealer. Special parameters such as the element counts, microstructure, grain size, inclusions count, etc. were inspected using quantitative metallography.

To simulate the true orthogonal cutting conditions, special specimens were prepared. After being machined to the configuration shown in Fig. 7, the specimens were tempered at 180–200°C to remove residual stresses. The hardness of each specimen has been determined over the whole working part. Cutting tests were conducted only on the bars where the hardness was within the limits ±10%.

(2) *Machine*: A retrofitted Schaerer HPD 631 lathe was used. The drive unit motor was replaced with a 15 kW variable speed AC motor and the feed motor was replaced with a 5 kW variable speed AC motor. The motors are controlled individually by AC invertors. The AC invertors are designed to provide the required Volts/Hertz ratio, allowing the AC motors to run at their optimum efficiency and providing rated torque capability through the motor's rated base speed. The control section of the AC inventors consists of a control board with a 16-bit microprocessor and keypad interface with an 8-bit microprocessor.

(3) *Cutting tool*: A general purpose tool holder CTJNR2520L16 and cutting inserts made of C6 (8% Co, 15% TiC, 77% WC) general purpose carbide were used. The

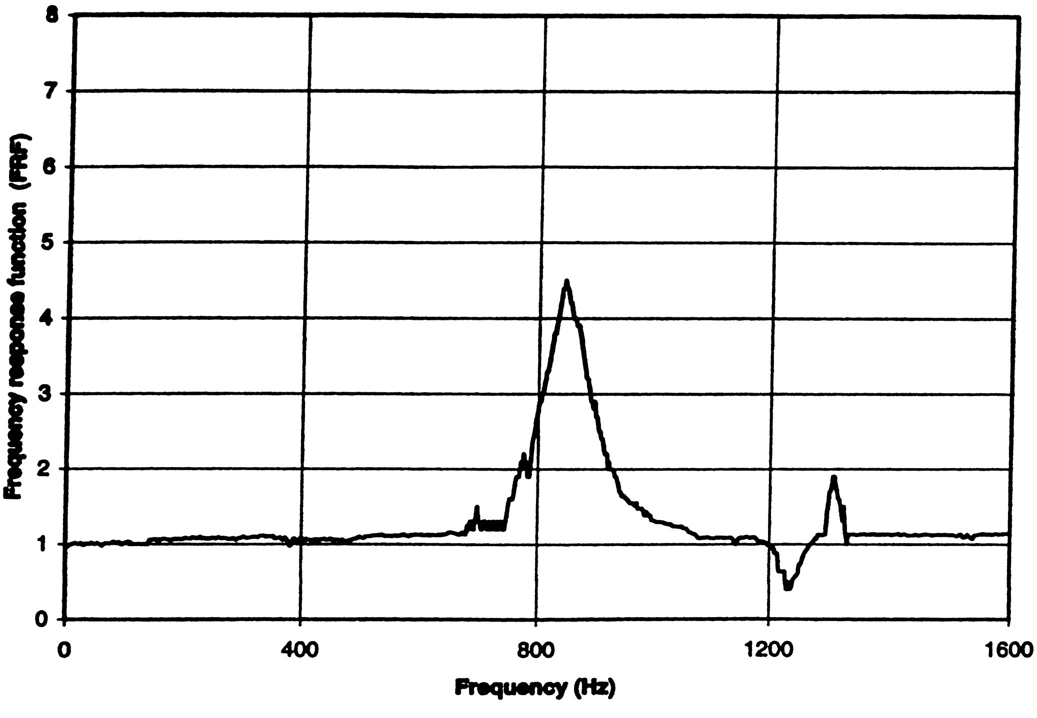

Fig. 9. Frequency response function of the thrust force signal vs. hammer signal.

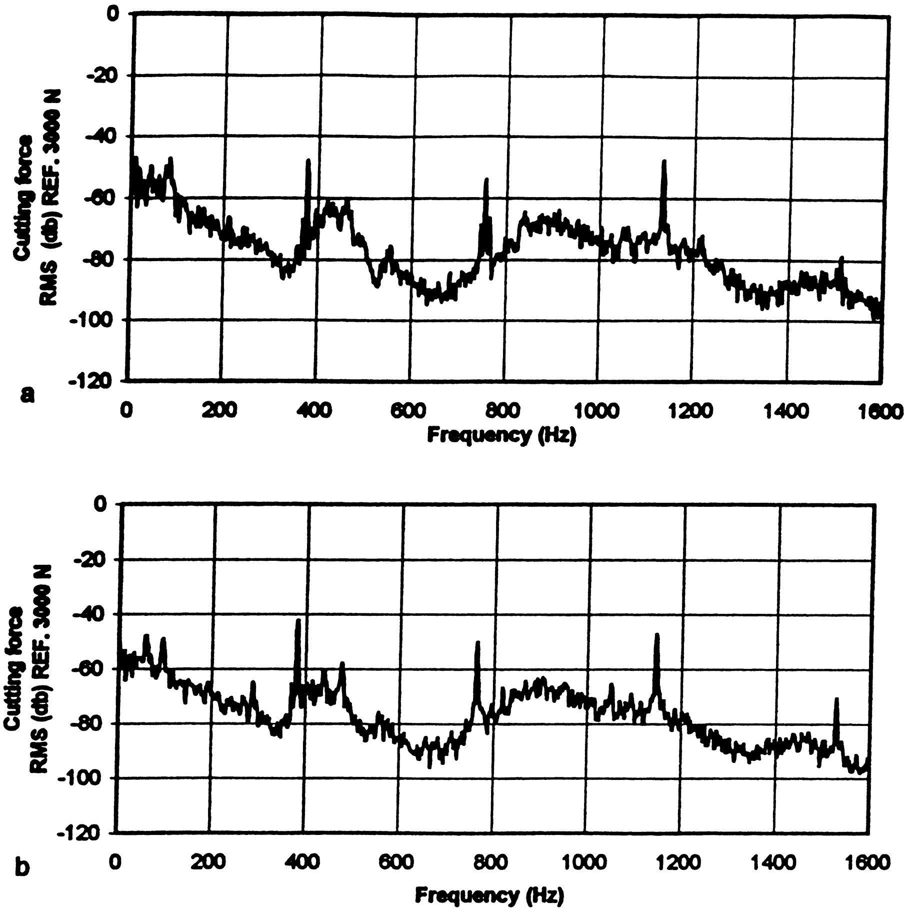

Fig. 10. Autospectra of the power component of the force: (a) n=250 rpm, f=0.15 mm/rev; (b) n=300 rpm; f=0.15 mm/rev.

geometry parameters of the tool were controlled according to American National Standard B94.50-1975. The tolerances for all angles were ±0.5 deg. The roughness R_a of the face and flanks did not exceed 0.25 μm and was measured according to American National Standard ANSI B46.1-1978. Each cutting edge was examined at magnification of 15x for visual defects such as chips or cracks.

(4) *Dynamometer*: A two-component dynamometer made similarly to Kistler Type 9271A was used. Based on the standard mounting as specified by the supplier (Kistler), the load washer (Kistler Type 9065) was mount on the workpiece spindle and pre-loaded to 120 kN. At this pre-load, the range for force measurements is from −20 to +20 KN.

(5) *Measuring set-up*: A schematic diagram of the set-up used in the experiments is shown in Fig. 8. The load washer was connected to the charge amplifier (Kistler, Mod. 5004) which, in turn, was connected to the FFT analyzer (B&K, Mod. 2032). Also, frequency response measurements of the set-up were carried out to determine the range of frequencies of the cutting forces that could be measured accurately without distortion. Fig. 9 shows the frequency response function vs. a hammer signal (Kistler hummer, Mod. 912). Referring to Fig. 9, it can be inferred that cutting forces of up to 650 Hz can be measured without any distortion due to resonance influences.

Analysis of the frequency composition was carried out to determine the variations in the cutting force. Fig. 10 shows autospectras for the power component of the cutting force. These were obtained using a shaker. A frequency sweep was carried out at a fixed load, and the magnitude of the ratio of the output of the dynamometer to the force applied by shaker was determined within the frequency range of 0–2 kHz. As seen, the frequencies of the character peaks in such autospectras are invariant of the chosen cutting regime. By this is meant that the dynamic rigidity of the set-up was sufficient, thus it did not affect the results of the study.

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