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INTERACTION BETWEEN DEFORMATION AND THERMAL WAVES IN METAL CUTTING

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ABSTRACT: In was proven in earlier studies that the chip formation process taking place in machining is cyclic and thus the forces and heat generated have cyclic nature. As a result, the deformation and thermal waves are generated in this process. This paper reveals that the interaction of the deformation and thermal coherent waves takes place in metal cutting. The destructive and constructive interference of these waves and its influence on the cutting force are discussed and the process parameters affecting this interference are determined. It is shown that the cutting speed affects the frequency of the waves, the cutting feed defines the phase difference and the depth of cut influences the location of the mean line of these waves. Comparison of the frequency of the energy waves in metal cutting with that of chip formation showed their coincidence. Using the results obtained in this study, the known great scatted in the reported data on the cutting force, foundation of high-speed machining, and the observed inconsistency in tool life are explained.

1. INTRODUCTION

In modern text books (for example, [1]) machining is identified as a deforming process that forms and shapes metals and alloys. Astakhov and Shvets [2,3] suggested and proved that the cutting process takes place in the cutting system consisting of the cutting tool, workpiece and

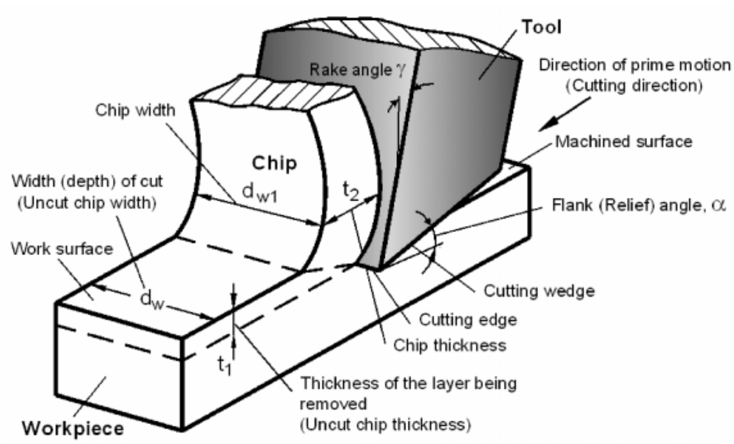

Figure 1: Components of the Cutting System

chip (Figure 1). The major systemic properties as the system time and dynamic interaction between system's components were used to reveal the essential characteristics of the cutting process. The chip formation process was proven to be of cyclic nature where the cutting force and temperature change within each cycle of chip formation causing the inherent dynamic nature of this process [3]. Therefore, the system interactions should be established, optimized and maintained to achieve the optimum performance of the cutting system.

The objective of this paper is to introduce and analyze the interaction of the deformation and thermal waves in the cutting system.

2. WORK DONE BY EXTERNAL FORCES AND THE INTERNAL ENERGY OF THE CUTTING SYSTEM

The energy supplied into the cutting system, U_{cs} is spent on the deforming of the workpiece and tool and on friction losses. Normally, the cutting tool deforms elastically while the layer to be remover on the workpiece undergoes cyclic elastic and the plastic deformation up to its fracture to form a new surface, which is the machined surface [3]. Friction losses take place at the tool-chip interface on the rake face and at the clearance face (flank surface) due to the elastic spring back of the work material. Therefore, the distribution of the input energy can be represented as

$$U_{cs} = W_{t-el} + W_{w-el} + W_{w-pl} + W_{f-r} + W_{f-c} \tag{1}$$

where $W_{t\text{-}el}$ is the energy spent on the elastic deformation of the cutting tool; $W_{w\text{-}el}$ and $W_{w\text{-}pl}$ are energies spent on the elastic and plastic deformation of the work material, respectively; $W_{f\text{-}r}$ and $W_{f\text{-}c}$ are friction loses on the tool rake and clearance contact faces, respectively.

Because metal cutting is the purposeful fracture of the layer to be removed [3], only those energy components of Eq. (1) spent to achieve this fracture are considered as to be useful in terms of achieving the major system objective. As seen they are $W_{w\text{-}el}$ and $W_{w\text{-}pl}$, i.e., only elastic and then plastic deformation of the layer to be removed lead to its fracture. As such, other components of Eq. (1) are regarded as energy losses.

A part of the mechanical energy spent on plastic deformation of the layer being removed as well as the energy spent on friction and plastic deformation on the rake and clearances faces convert into thermal energy or heat. This thermal energy should also be considered in the analysis of the cutting system. According to energy theory of failure, a given volume of the work material fails when the critical internal energy accumulates in this volume. This critical internal energy can be of any kind or the sum of different input energies [4]. This postulate referred to as the internal energy principle is used in this work. Therefore, the internal energy of the cutting system has to be considered and particular attention is to be paid to the energy accumulated in the layer being removed just in the front of the cutting edge. As such, an increment of the internal energy of this layer can be represented as the sum of the mechanical energy supplied from outside, dA and thermal energy generated in the system, dQ, i.e.

$$dW_{in} = dA + dQ \tag{2}$$

3. INTERACTION BETWEEN DEFORMATION AND THERMAL WAVES IN THE MACHINING ZONE

3.1 Internal Energy Principle

According to the second law of thermodynamics [5], thermal energy does not flow from regions having lower temperatures to those having higher temperatures. Because the machining zone (a small zone around the cutting edge where elastic and plastic deformations of the layer being removed take place) is a heat source, its temperature is higher than that of the rest of the work material. As a result, the heat energy should flow from this zone so it seems that the sign "–" should be assigned to the second terms of Eq. (2). However, it can be demonstrated that the sign "+" before term dQ in Eq. (2) can be justified in the metal cutting system. Because the machining zone moves with a certain velocity with respect to the workpiece, the thermal energy can enter into the layer being removed if and only if the velocity of heat transfer exceeds that with which the machining zone moves over the workpiece. The heat realized at a given instant in the machining zone forms a certain dynamic energy field in the workpiece around the machining zone at the considered instant. As such, there is no priority direction of heat transfer exists, i.e. heat transfers in all directions at the same rate. A region on the workpiece over which the cutting system moves at the considered instant is therefore a decaying heat source. Heat transfers from this source and so an increment of heat energy, dQ is the residual heat transferred in the considered location of the cutting system from the previous position of this system providing that heat transfers faster that the cutting system moves from the previous position to the current.

The relative velocity of a moving heat source is characterized by the Peclet number, which can be represented in terms of machining process parameters as follows [3]

$$Pe = \frac{va_1}{w_w} \tag{3}$$

where, v is the velocity of a moving heat source (the cutting speed) (m/s); a_1 is the uncut chip thickness (m); and w_w is the thermal diffusivity of the work material (m^2/c).

When Pe > 10, the heat source (the cutting tool) moves over the workpiece faster than the velocity of thermal wave propagation in the work material so that the relative influence of the thermal energy generated in cutting on the plastic deformation of the work material is only due to the residual heat from the previous tool position. This is the case for the values of terms of Eq. (3) used in practice of metal cutting. The calculations known show that in many cases, the velocity of the cutting system exceeds that of heat transfer in the same direction. However, this is true only for the pure orthogonal cutting, where the tool never passes the same, or even the neighboring point of the workpiece more than once (Figure 1). In practical machining operations (turning, milling, drilling, etc.), the feed is used to generate the machined surface (Figure 2). As such, the cutting tool advances into the workpiece with the feed velocity, which is considerably smaller than the cutting velocity so that the residual heat from the previous pass might significantly affect the cutting process on the current pass. The smaller the time interval between the two successive tool positions (i.e. with smaller workpiece diameter and higher cutting speed), the greater the effect of the residual heat. As such, the "+" sign of the term dQ in Eq. (3) does not contradict the second law of thermodynamics, i.e. first the heat moves into a region having lower temperature and then the cutting system moves into the same region.

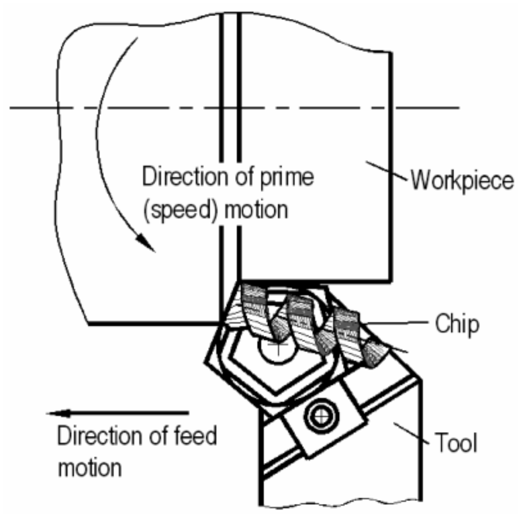

Figure 2: Turning

The current discussion suggests that that the feed velocity, v_f (in turning, it calculates as $v_f = fn$ (m/s), where f is feed per revolution (m/rev) and n is rpm of the workpiece (tool)) should be compared with the velocity of heat conduction, v_q. Such a comparison suggests that if $v_f = v_q$ then the maximum heat energy enters the cutting system and thus the residual heat has the strongest influence on the cutting process.

According to the internal energy principle, the energy of failure (fracture) of the layer to be removed is constant under given machining conditions so according to Eq. (2), less mechanical energy (dA) is needed for the fracture of the layer being removed when more heat energy (dQ) is available in the current position of the cutting system.

3.2 Coherence Energy Waves

In is conclusively proven [2,3] that the chip formation process is cyclic, and thus the cutting force and the thermal energy generated in metal cutting change within each cycle of chip formation. The frequency of chip formation is proven to be dependant on cutting speed and on the work material (Fig. 2.18 in [3]). Therefore, this process generates the deformation and thermal waves. Because these two are generated by the same source, namely, the chip formation process (or simply – tool), these waves must be coherent.

To comprehend the concept of interaction of coherent energy waves, simple turning is considered as an example. In turning, the internal energy in the layer being removed increases according to Eq. (2) due to heat conduction in the feed direction (Figure 2). As the workpiece completes one revolution, the thermal energy, generated at the previous position of the cutting system, reaches the current position of this system. Calculations show that the cutting speed significantly exceeds the velocity of heat conduction, while the feed rate (feed velocity) commensurates with this velocity.

Since the intensity of a decaying heat source obeys the normal law, the distribution curve transforms into an almost straight line with time τ as shown in Figure 3, where the instants of consideration are as follows: $\tau_1 < \tau_2 < \tau_3$. Physically, it means that a certain nearly constant temperature field establishes within the considered volume with time. If the feed rate (v_f) is equal to the velocity of heat conduction (v_q), the maximum thermal energy is supplied into the cutting system. However, if $v_f > v_q$, then $dQ = 0$ and, if $v_f < v_q$, then the heat energy supplied to the cutting system is less than maximum (Figure 3).

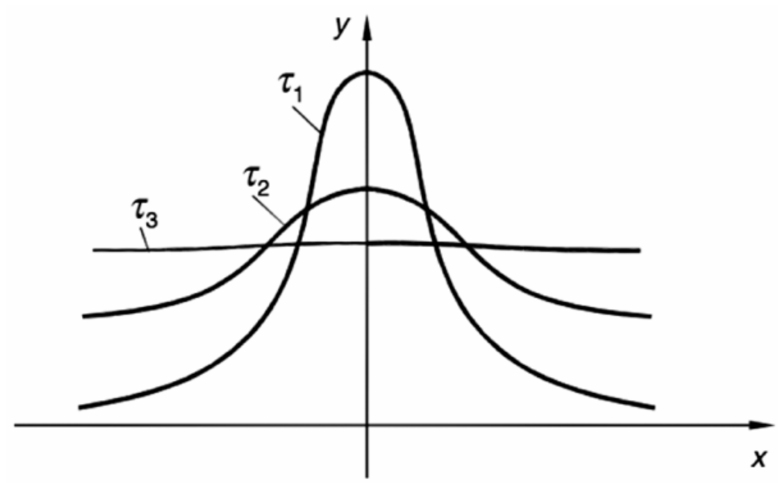

Figure 3: Intensity of a Decaying Heat Source

According to the internal energy principle, the energy of failure (fracture) of the layer being removed is constant under given machining conditions. The time interval between two successive tool positions (between neighboring trajectories of the cutting tool) depends on the cutting speed v and the diameter of the workpiece D_w and is calculated as

$$\tau = \frac{\pi D_w}{v} \tag{4}$$

Table 1 shows the results of the calculations of the time intervals for two different diameters of the workpiece. If the cutting tests are conducted under the conditions indicated in Table 1, each combination of parameters should result in different consumption of mechanical energy. This fact can be verified by using the measurements of the cutting force because this mechanical energy is calculated as

$$A = F_z v \tau \tag{5}$$

where F_z is the power component of the cutting force [3].

Table 1
Feed Velocities and Time Difference Between Two Successive Positions of the Cutting Tool

v (m/s)	d_w = 80 mm		d_w = 100 mm	
	$v_f \cdot 10^{-3}$ (m/s)	τ (s)	$v_f \cdot 10^{-3}$ (m/s)	τ (s)
1	0.28	0.25	0.22	0.31
5	1.39	0.05	1.11	0.063

According to Truesdell and Noll [6], a wave is considered as the means by which a given system moves from one state to another with a finite velocity. It is also known that energy moves in waves. Thermal waves formed at the preceding position of the cutting system move in the workpiece in the feed direction with a certain velocity, which depends only on the properties of the work material (its thermal diffusivity) and hence this velocity is constant for a given work material. Reaching the current position of the cutting system, these waves interact with those due to deformation. Since the thermal energy in the system is a part of the mechanical energy transformed, their frequencies should be the same.

Different feeds should result in phase differences between the mechanical and thermal waves. As a result, maximum reinforcement (or constructive interference) of the mechanical and thermal waves takes place when they have the same phase, while maximum destructive interference takes place when their phases are opposite. It is clear that a number of intermediate states are possible depending on a particular phase difference.

The phase difference exists between the two neighboring trajectories (threads) of the moving cutting edge. As such, a decaying heat source generates thermal waves at the previous trajectory, while the cutting edge at the current trajectory generates a deformation wave. The distance between the neighboring trajectories (feed per revolution) is the path difference of the waves considered. As indicated in [7], the interaction of such longitudinal waves results in the reinforcement of energy (constructive interference) when these waves are in-phase, i.e., when the path difference, represented by the feed, is

$$f = \frac{1}{2} 2kl_0, \quad k = 0,1,2,... \tag{6}$$

where l_0 is the wavelength.

On the contrary, when the path deference is

$$f = \frac{1}{2}(2k+1)l_0, \quad k = 0,1,2,... \tag{7}$$

these waves have opposite phases which results in their destructive interference.

The physical picture discussed is illustrated in Figure 4, where external bar turning and the corresponding cutting tool trajectory are shown. Let us consider a microvolume of the work material located at Point 2 on the tool trajectory (Figure 4b) at the instant when the tool passes this point.

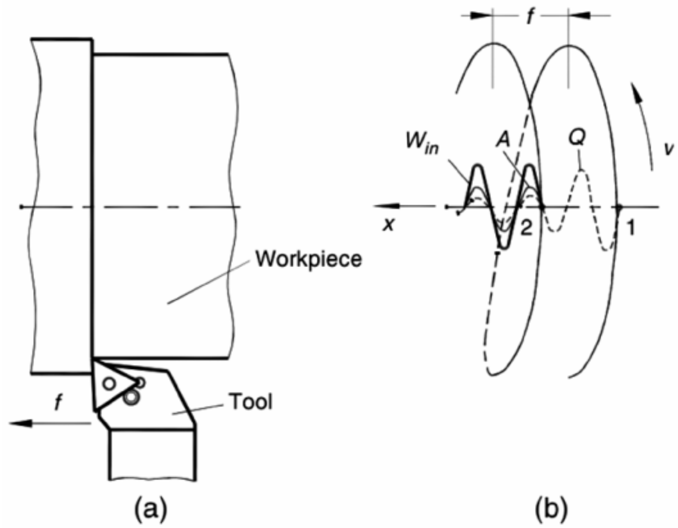

Figure 4: (a) External Bar Turning and (b) The Trajectory of the Cutting Tool

According to Eq. (2), a change in the internal energy (dW_{in}) of the microvolume is the sum of the mechanical work done by the external forces (dA) applied by the tool and the residual heat energy (dQ) the current position from the identical volume located on the neighbouring trajectory of the tool (from Point 1, Figure 4b). As shown, the residual heat dQ in Eq. (2) is positive because this heat is transferred into the microvolume at Point 2 (when the cutting tool reaches there) from the decaying heat source of Point 1 (the preceding position of the cutting tool), if and only if the velocity of heat conduction in the workpiece is equal to or greater than the translation speed of the cutting system along the feed direction (the x direction in Figure 4b). Consider a typical example: workpiece material: AISI steel 1045 having thermal diffusivity $w_w = 6.75 \times 10^{-6}$ m²/s, cutting speed ν = 180m/min, cutting feed f = 0.15mm/rev, workpiece diameter D_w = 100 mm, tool cutting edge angle $\kappa_r = 60^o$. As such, the uncut chip thickness $t_1 = f \sin \kappa_r = 0.15 \sin 60^0 = 0.13$mm and the feed velocity (which is the velocity of the heat source) $v_f = nf = \frac{10^3 v}{\pi D_w} f = \frac{10^3 \cdot 180}{3.141 \cdot 100} 0.15 \cdot 10^{-3} \approx 0.086$m/min or $v_f = 0.00143$m/s. Substituting v_f, a_1, and w_w into Eq. (3), one can calculate Pe = 0.0275. As Pe < 10, there is no contradiction with the laws of thermodynamics in Eq. (2) - first heat enters to the less heated zone (Point 2, Figure 4b) and then the cutting tool (as a heat source) moves there, thus the residual heat in Eq. (2) is positive.

4. EXPERIMENTAL VERIFICATION

The experimental verification of the internal energy principle formulated and interactions of the coherent waves discussed was carried out using a turning test. Hot rolled bar stock of steel AISI 4140 was used as the workpiece. Since the dynamic parameters of metal cutting are known to be very sensitive to even small changes in the cutting process, special attention was paid to the selection of the conditions of the tests and to the experimental methodology which was selected according to the requirements presented in [3]. The actual (as tested upon receiving) chemical composition was: 0.39% C, 0.72% Mn, 0.012% P, 0.001% S, 0.31% Si, 1.03% Cr and 0.16% Mo. The hardness of the work material was 221 HB. A retrofitted Schaerer HPD 631 lathe was used as the test machine.

A 2-component Kistler Type 9271A dynamometer was used. Based on the standard mounting as specified by the supplier (Kistler), the load washer (Kistler Type 9065) was installed in the dynamometer and pre-loaded to 120 kN. At this pre-load, the range for force measurements is from -20 to + 20 KN; threshold is 0.02 N; sensitivity is -1.8 pC/N; linearity does not exceed a range of ± 1.0 %FSO; overload is 144 kN; cross talk does not exceed 0.02 N/N; resonant frequency is 40 kHz; temperature error does not exceed +30 N/^{o}C. The load washer was connected to the dual mode charge amplifiers (Kistler, Mod. 5010B). The static and dynamic calibrations were performed according to the methodology presented in [3].

Four general purpose triangular cutting inserts (ANSI designation TCMT-110204) made of P20 carbide from four different carbide suppliers were selected for the test to avoid bias due to particular carbide properties. These are numbered 1, 2, 3 and 4.

Influence of the cutting speed. The test results with insert No.1 are shown in Table 2. Following the conventional way suggested in earlier studies [8,9], correlations between the cutting speed and cutting force were expressed by the simple power curve relation

$$F_z = Cv^x \tag{8}$$

where C and x are constants.

Table 2
Experimental Results (Insert No. 1)

Cutting Speed v(m/s)	Cutting Force F_z(N) t_1 = 0.1mm	Cutting Force F_z(N) t_2 = 0.5mm	Cutting Force F_z(N) t_3 = 1.0mm
0.07	84	328	506
0.11	75	244	469
0.23	47	206	469
0.29	38	206	375
0.46	38	169	375
0.58	56	169	394
0.72	47	178	469
0.92	41	178	450
1.15	47	169	469
1.82	56	187	431
2.30	56	187	469
2.63	60	178	431
4.60	38	169	375
5.76	53	187	366

Using the experimental results obtained (Table 2), the following relationships were obtained:

$$F_z = 53.94v^{-0.1} \quad \text{when} \quad t_1 = 0.1\text{mm} \tag{9}$$

$$F_z = 193.13v^{-0.1} \quad \text{when} \quad t_1 = 0.5\text{mm} \tag{10}$$

$$F_z = 427.79v^{-0.1} \quad \text{when} \quad t_1 = 1.0\text{mm} \tag{11}$$

The current consideration, however, suggests another type of representation of the experimental results. The experimental points from Table 2 were placed in the orthogonal coordinate system "v – F_z." With regard to the aforementioned wave nature of deformation, these points were considered as sinusoidal periodic data (Figure 5) that can be represented mathematically as

$$F_z = F_{z0} + F_{za} \sin\left[\frac{2\pi}{l_v}\left(v + v_{ph}\right)\right] \tag{12}$$

where F_{z0} is the mean of the sine wave, F_{za}, l_v and v_{hp} are its amplitude, wavelength, and initial phase, respectively.

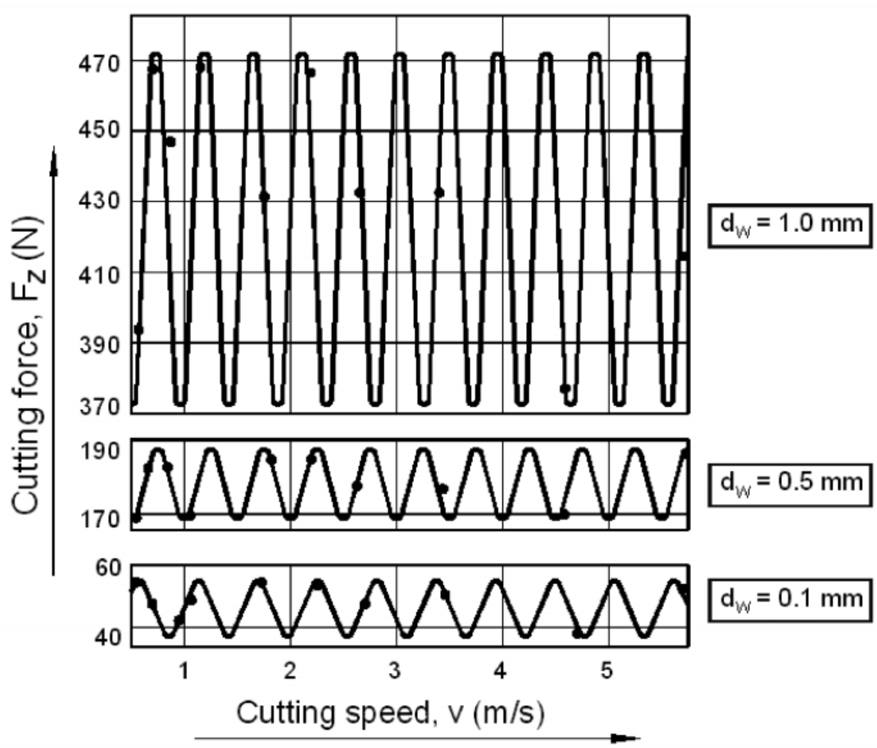

Figure 5: Experimental Results Represented as Sinusoidal Periodic Data in the Coordinate System "v – F_z".

The proposed representation of the data of Table 2 results in the following models:

$$F_z = 47 + 10\left[\frac{2\pi}{0.56}(0.050 + v)\right] \quad \text{when} \quad d_w = 0.1\text{mm} \tag{13}$$

$$F_z = 178 + 11\left[\frac{2\pi}{0.50}(0.049 + v)\right] \quad \text{when} \quad d_w = 0.5\text{mm} \tag{14}$$

$$F_z = 422 + 50\left[\frac{2\pi}{0.46}(0.045 + v)\right] \quad \text{when} \quad d_w = 1.0\text{mm} \tag{15}$$

The experimental results have also shown that the wavelength of the sine wave l_v decreases with the depth of cut. Particularly, when the depth of cut d_w = 0.1mm, the wavelength of the corresponding sine wave approximates the experimental results l_ν = 0.56m/s and when d_w = 1.0mm, this wavelength becomes l_v = 0.46m/s.

Table 3 shows the results of tests conducted under the same conditions with insert No. 2. The comparison of these results (solid lines) with those obtained using insert No.1 (dashed lines) is shown in Figure 6. As shown, the wavelength and the amplitude remain the same while the position of the mean line and the initial phase are shifted. The experimental data obtained allow us to conclude that, under the given cutting regime and tool geometry, the wavelength and the amplitude of the sine wave are determined by the properties of the work material, while the amplitude and the initial phase are determined by the processes taking place at the tool contact surfaces. The latter is evident because the use of insert No. 2 instead of insert No. 1, changed only the contact processes on the tool rake and flank faces due to the difference in the chemical composition of insert materials, surface condition and finish, etc., while the other parameters of the cutting system remained the same.

Table 3
Experimental Results (Insert No. 2)

Cutting Speed v(m/s)	Cutting Force F_z (N)		
	t_1 = 0.1mm	t_2 = 0.5mm	t_3 = 1.0mm
2.80	66	187	394
3.03	66	225	394
3.30	38	221	403
4.18	75	206	394
4.27	51	206	394
4.45	75	216	375
5.25	79	234	403
5.33	71	216	394

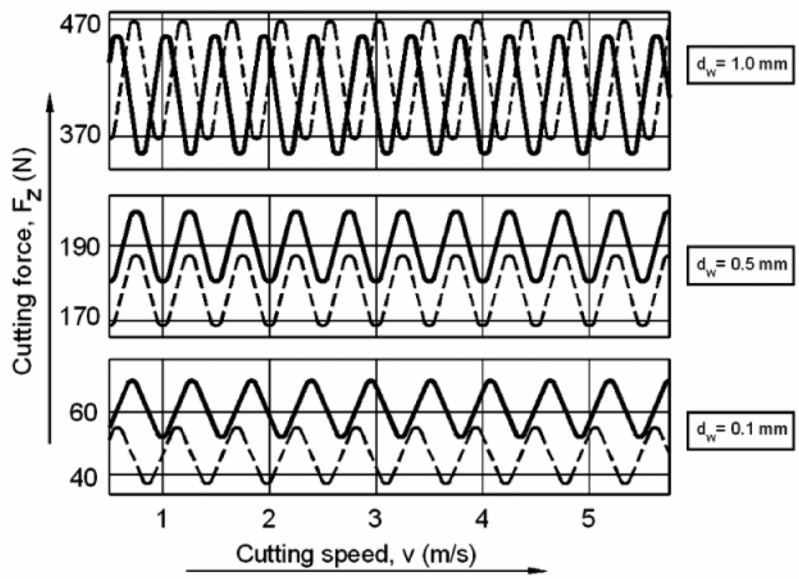

Figure 6: Scatter for Cutting Inserts No. 1 and No. 2

Figures 5 and 6 suggest that the cutting force changes sinusoidally with the cutting speed when other cutting conditions remain the same. This suggestion was verified as follows. A particular sine-wave shape was established under these conditions – cutting feed f = 0.12mm/rev and depth of cut d_w = 0.5mm (Tables 2 and 3) – as

$$F_z = F_{za}\sin\left(\frac{2\pi}{l_v}v\right) = 11\sin\left(\frac{2\pi}{0.5}v\right) \tag{16}$$

Then, cutting tests were carried out with insert No. 3 and insert No. 4 using the same cutting conditions. The corresponding experimental points were placed in the coordinate system "v – F_z" and the initial phase of the sine curve described by Eq. (16) was determined. Figure 7 shows that the experimental points fit this curve fairly good, accounting for the accuracy with which the cutting force can be measured.

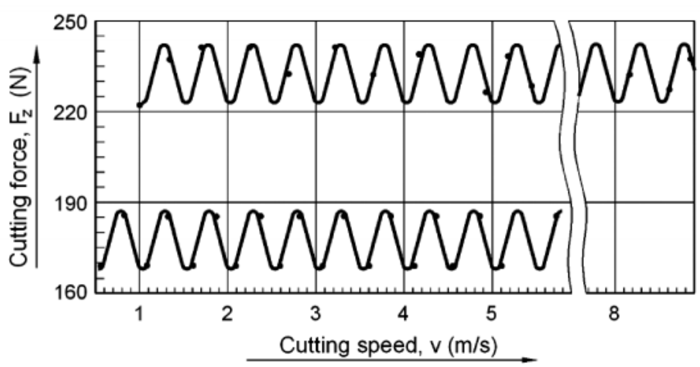

Figure 7: Experimental Results for Cutting Inserts No. 3 and No. 4

The experimental results show that the cutting force changes sinusoidally with the cutting speed. If the tool geometry and location of the cutting tool with respect to the workpiece surface are kept constant, the energy of failure (fracture) of the layer to be removed remains constant too. Therefore, according to Eq. (2), the mechanical energy required should be a function of the cutting speed. If the interaction of deformation and thermal waves causes their reinforcement then the required mechanical energy decreases. On the contrary, if this interaction results in destructive interference, the required mechanical energy increases.

When the cutting feed is constant, the path difference of the coherent waves does not change. According to Eq. (2), a change in the cutting speed results in the change in the time interval between the two successive tool positions (between the neighboring trajectories of the cutting tool), which is, according to Eq. (2), equivalent to a change in the intensity of the heat source. Therefore, it becomes clear that the revealed dependence of the interaction of the energy waves on the cutting speed is possible only if the frequency of deformation and heat waves depends on this speed.

The phenomenon of interaction of the deformation and thermal longitudinal waves was additionally examined using the following logic: the interaction of the waves takes place due to the fact that these waves are coherent. Therefore, if the coherence of the waves is disturbed, the interaction should not be observed. To verify this statement, the second series of experiment was carried out using face cutting (Figure 8a). Table 4 lists the ranges of the cutting parameters used in the test. Other parameters of the cutting system and the measuring rig were kept the same.

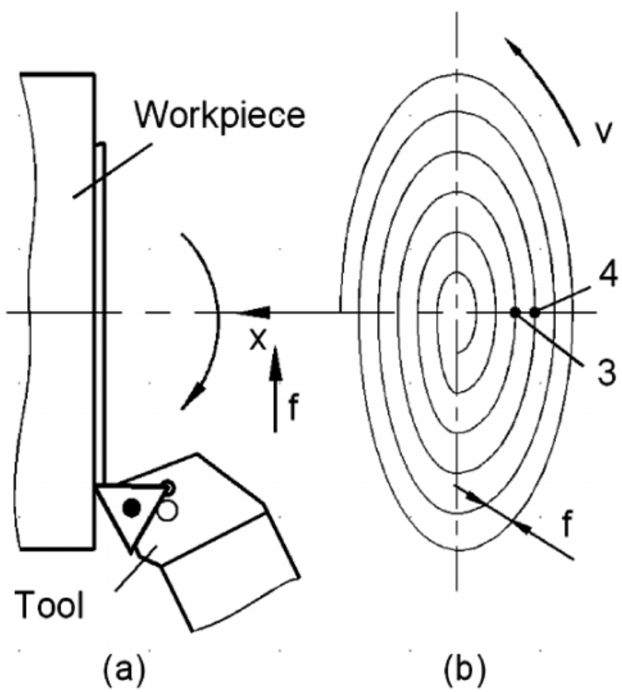

Figure 8: (a) Face Cutting and (b) The Trajectory of the Cutting Tool

Table 4
Ranges of Values of Cutting Parameters for the End Turning Tests

Parameter	Low Value	High Value
Workpiece diameter (mm)	60	120
Cutting speed (m/s)	0.15	4.00
Feed (mm/rev)	0.07	0.25
Depth of cut (mm)	0.10	3.00

The experimental results obtained in this test show that no force variation has been observed over a considerably wide range of cutting conditions. This result can be explained as follows: in face cutting, the cutting speed is not constant but differs for each successive point of the tool trajectory (Figure 8b). Therefore, the thermal wave generated on the neighboring trajectory of the cutting tool (Point 3) does not affect the cutting force (energy consumption) on the current trajectory (Point 4), because this thermal wave has been formed at different cutting speeds and, therefore, the deformation and the thermal waves are not coherent. Hence, the results prove that, on the one hand, the cutting speed affects the wavelength, while on the other hand, the interaction of the energy waves is a real phenomenon of the cutting process.

The correlation of the wavelengths under different cutting speeds that result in the maximum reinforcement of the coherent waves can also be established using the following considerations. It follows from Eqs. (2.69) and (2.70) that, if the cutting feed is kept constant, the reinforcement (constructive interference) and destructive interference of the total energy flux are possible only when the wavelength is a function of the cutting speed, i.e. when $l_o = f(v)$ is the case. If a certain i-th crest of this function takes place when $f = kl_i$, then the next crest appears when the number of waves increases by 1, i.e. when $f = (k + 1)l_{i+1}$. Consequently, if the cutting force varies according to a sinusoidal function with the cutting speed,

$$l_{i+1} = \frac{l_i}{1 + l_i / f} \tag{17}$$

Influence of cutting feed. When the path difference (the cutting feed) remains constant, a change in the cutting speed causes a periodic increase and decrease of the cutting force due to the variation in the frequencies of the energy waves generated at different cutting speeds (the velocity of deformation). If this happens due to the interference of the energy waves discussed, a change in the cutting feed should also affect the cutting force because the cutting feed defines the path difference.

However, force F_z is affected not only by the wave-interaction force component $F_s(f)$ but also by the force component $F_0(f)$, which depends on the uncut chip thickness because the uncut chip thickness changes with the cutting feed [3]. Mathematically, it can be represented by analogy with Eq. (12) as

$$F_z = F_0(f) + F_s(f) = F_0(f) + F_a \sin\left[\frac{2\pi}{l}(f + f_{ph})\right] \tag{18}$$

It the wavelength, l_{v1} of the sine wave which approximates variation of the cutting force, P_z with the cutting speed, v, and the frequency of the coherent waves l_1 are known for cutting speed v_1 then accounting Eq. (17), the wavelength l_k for any other cutting speed which differs from v_1 by a number divisible by the l_1 can be found as follows

$$l_k = \frac{fl_1}{f + l_1(k-1)} \qquad \text{where} \quad k = 2,3,\ldots, n \tag{19}$$

Points (l_i, v_i) calculated using Eq. (19) can be approximated by a line so that the wavelength of the deformation wave corresponding to any cutting speed, v can be calculated knowing v_1, l_{v1}, and l_1 (providing that the cutting feed, f remains invariable) as

$$l = \frac{1}{1/l_1 + (v - v_1)/(fl_{v1})} \tag{20}$$

The third series of experiment was carried out using the same experimental conditions. The workpiece diameter was 88mm, the depth of cut t_1=0.1mm. The cutting force, F_z was measured as a function of the cutting feed, f under different rotation speeds of the workpiece, n. The experimental result for v=2.9 m/s, 2.3 m/s, 1.8 m/s, 1.4 m/s, 1.2 m/s, and 0.9 m/s are shown in Table 5.

Table 5
Experimental Results (Series No. 3 of Experiments)

f	v = 2.9 m/s		v = 2.3 m/s		v = 1.8 m/s	
(mm/rev)	F_z (N)	F_s (N)	F_z (N)	F_z (N)	F_z (N)	F_s (N)
0.070	75	–2.84	56.2	–3.05	56.2	–0.01
0.074	84	3.91	60.0	–2.06	60.0	1.67
0.084	81	–4.70	71.2	2.29	65.6	2.11
0.097	94	1.00	76.9	–1.06	71.2	1.00
0.110	103	2.68	84.4	–2.53	75.0	–1.98
0.120	103	–2.94	93.7	–0.05	84.4	2.21
0.130	112	0.40	103.1	2.42	90.0	2.26
	F_0 = 38.5 + 562f		F_0 = 11 + 690f		F_0 = 20 + 518f	
f	**v = 1.4 m/s**		**v = 1.2 m/s**		**v = 0.9m/s**	
(mm/rev)	**F_z (N)**	**F_s (N)**	**F_z (N)**	**F_s (N)**	**F_z (N)**	**F_s (N)**
0.070	0.070	–2.81	54.4	2.11	56.2	3.98
0.074	0.074	4.29	58.1	3.40	56.2	1.54
0.084	0.084	2.37	61.9	1.05	52.5	–8.32
0.097	0.097	–1.25	71.2	2.48	76.9	8.11
0.110	0.110	2.63	75.0	–1.74	80.6	3.92
0.120	0.120	–3.04	78.7	–4.07	88.1	5.30
0.130	0.130	4.41	93.7	4.82	96.6	6.69
	F_0 = 10 + 567f		F_0 = 9.5 + 611f		F_0 = 9.5 + 611f	

The graphical analysis of the experimental results shown in Table 5 showed that the maximum and minimum of F_z locate in the "f – F_z" coordinate system on two inclined parallel lines. Therefore, the mean of the sine wave (for the experimental conditions considered) is a straight line $F_0(f) = C_1 + C_2 f$. Constants C_1 and C_2 were determined using the experimental data so the position of the sine wave means were determined for each test (Tables 5). Then, using Eq. (18), the sinusoidal component of P_z was calculated as

$$F_s(f) = F_z(f) - F_0(f) \tag{21}$$

The experimental points for each cutting (deforming) speed were placed in the "f–P_s" coordinate system. Then a sine wave was found using a specially developed curve-fitting program for the best approximation of the experimental points. Some results are shown in Figure 9. As such, for the cutting speeds in Table 5, the wavelengths of the energy waves (deformation and thermal) were determined. The results are as follows: 6.3, 6.5, 7.0, 7.6, and 7.8 μm. To confirm the validity of Eq. (20), the initial cutting speed was selected to be v_1 = 0.9 m/s and thus l_{v1}=0.56 and l_1=7.8 μm. Using Eq. (20), the wavelengths for other cutting speed were calculated with the following results: 6.336, 6.723, 7.033, 7.348, and 7.78 μm. A fairly good agreement between the calculated and the experimentally obtained results proves that energy expands in a solid in waves. The wavelength of these waves depends on the velocity of deformation and can be determined experimentally. Moreover, a comparison of these result with the frequency of chip formation obtained for the same conditions (Fig. 2.18 in [3]) shows that these waves were generated by the chip formation process.

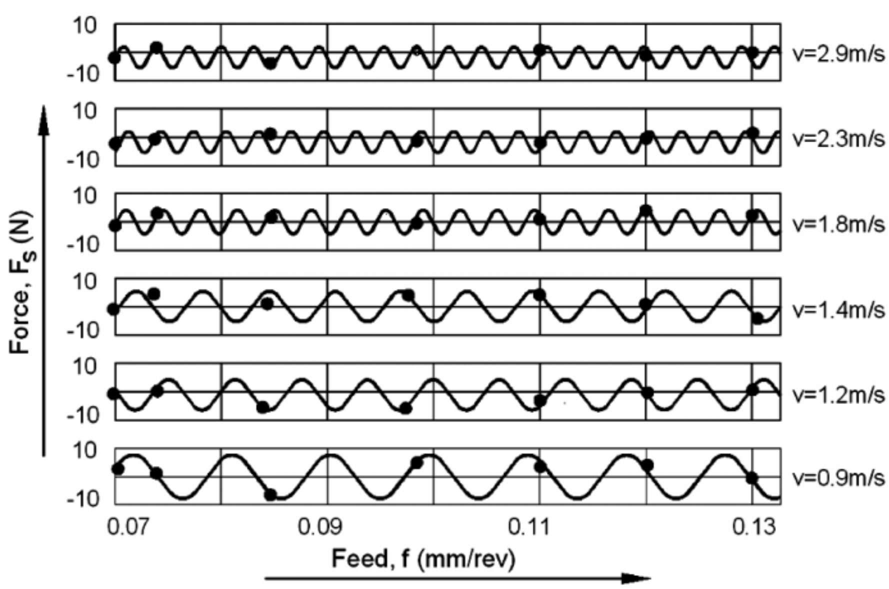

Figure 9: Sine Wave Approximation of the Experimental Data in the Coordinate System "f – F_z"

To prove that the parameters of the discusses waves do not correlate with the rotational speed of the workpiece or with other velocities of the moving parts of the machine tool, a special test was carried out. It was found from the previous experiments that parameters F_0 and v_{ph} are very sensitive to even small changes in the cutting process [3]. On the contrary, parameters F_a and l_v depends only on the cutting regime. Accounting for these facts, the methodology of the current experiment was developed to be as follows. A stepped workpiece having shoulders of different diameters was first turned on the smallest diameter using cutting speed 2.4 m/s and parameters of F_{a1} and l_{v1} were determined for this case. Then, the next shoulder was turned keeping the same setup and the cutting speed thus reducing spindle rpm. As such, parameters of F_{a2} and l_{v2} were calculated using the experimental results. Then, the third shoulder of greater diameter was machined keeping the same conditions including the cutting speed (thus smaller rpm). Again, parameters of F_{a3} and l_{v3} were determined. Because these parameters are found to be the same for all three runs, it was concluded that they depend only on the cutting speed and do not correlate with particular testing peculiarities.

6. DISCUSSION AND CONCLUSIONS

Importance of the interaction of deformation and thermal waves in metal cutting. The high energy rate and cyclic nature of the chip formation process in metal cutting result in the generation of deformation and thermal waves. Because these waves are generated by the same source, namely, the chip formation process (cutting tool), they are coherent and their interference takes place in the cutting process. This interference affects the amount of external energy required since, according to the von Mises' criterion of failure with physical meaning given by Hencky, the critical value of the distortion energy (the total strain energy per unit volume) is constant for a given workpiece material. The revealed existence of interference explains the unexplained phenomena of the metal cutting process:

- Great scatter in the reported data on cutting force. Even the very similar cutting conditions and extraordinary care taken while performing experiments, the scatter exceeds 50% (for example, [10]).
- Foundation of high-speed machining. When the cutting speed increases, the volume of work material removed per unit time also increases so that the energy spent in cutting should increase. Moreover, an increase in the cutting speed leads to the corresponding increase in the strain rate in the chip formation zone. Oxley [11], this rate is in a range from 10^3 to 10^5 s^{-1}or even higher in metal cutting. The available data on materials testing at high (for example, [12]) show that the shear flow stress increases dramatically for many common materials when the rate of strain exceeds 104. Knowing these facts, one might expect a significant increase in the cutting force when the cutting speed increases. Particularly, the difference should be very significant at high cutting speeds in the so-called high-speed machining. The practice, however, shows that opposite is the case. Zorev [8] studied a number of work materials (from low- to high-carbon steel, low and high alloyed steels) at low and high cutting speeds and conclusively proved that the cutting force decreases (at different rates for different work materials) with an increase in the cutting speed. Moreover, the results of multiple studies on the cutting force in high-speed machining (for example, [14]) show a significant decrease (30-40%) in the cutting force at high cutting speed, and thus rates of strain. The results presented in this paper resolve this known contradiction. When

the cutting speed increases, the time interval between two successive tool positions (Points 1 and 2 in Figure 4) decreases. As such, higher thermal energy adds to the total energy needed for the fracture of the layer being removed. As a result, the cutting force decreases. Poor reproducibility of the high-speed machining results and inability to reproduce the results obtained by other researched [14] can easily be explained by the described wave interference phenomena.

- Inconsistency in tool life. The resource of the cutting tool is defined as the limiting amount of energy that can be transmitted through the cutting wedge (defined as a part of the tool located between the rake and the flank contact areas) until it fails [4]. Great inconsistency in tool life, known to the specialists in the field, can be easily explained by the described wave phenomena because the energy transmitted through the cutting wedge depends on the interaction of the deformation and thermal waves in the machining zone.

The obtained results offer a novel approach to the selecting the optimal cutting regime in machining, particularly, high-speed machining. This regime should be selected so that the constructive interference of energy waives results in their maximum reinforcement to reduce the energy needed to accomplish the process and to increase tool life. At higher strain rates and cutting speeds, the benefits of the proposed approach are more significant.

The experiments reveal that:

- Under practical machining conditions, the velocity of heat conduction is less than that the velocity of the heat source (tool) and thus the heat generated in the deformation zone can affect the cutting parameters only by the residual heat from the neightbouring tragectory of the tool.
- The deformation and the thermal waves are coherent as generated by the same source, namely the chip formation process and thus their frequency coinside with that of this process. Changing phase difference of these waves, one can change the cutting force and thus all correlated parameters of the cutting process.
- The cutting feed determined the phase difference of the energy waves, the cutting speed affects their frequency, the depth of cut affeects the position of the mean lines of the deformational and thermal sine waves. The study offers a simple experimental method to determine the parameters of the deformation wave.

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