Investigation of the Mechanism of Chatter Formation during Metal Cutting Process

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Abstract :

Experiments have been carried out to determine the physical nature and characteristics of the unstability of metal cutting process for different pairs of work and tool materials and their influence on chatter formation. Also the influence of the characteristics of various parameters of the elastic system of machine-tools and conditions of machining on chatter have been considered. Experimental results enabled the discovery of the mechanism of chatter formation and determination of stable cutting conditions.

Introduction :

The machining of metals is often accompanied by a violent relative vibration between work and tool which is called chatter. Chatter is undesirable because of its adverse effects on surface finish, machining accuracy, life of tool and machine parts, and workers health due to intensive noise created by chatter. Further more, chatter is also responsible for reducing output because, if no remedy can be found, metal removal rates have to be lowered until vibration-free performance is obtained.

Unlike other forms of vibration phenomenon occuring under practical conditions such as free vibrations (induced by shock) and forced vibrations (induced by unbalanced effects, gear and bearing errors, etc.) either arising in the machine itself or transmitted through the foundation from other machines; the physical causes of chatter are still not fully understood (1).

Although this topic is enligtened by a good number of research works all over the world a unique view on the physical causes of chatter is still absent. This is why, it is extremely difficult to find any remedy short of reducing metal removal rates with consequent lowering of output.

Results of preliminary experiment have shown that, chatter unlike other forms of free vibration is accompanied by a negative damping force. This is possible only if there is a generating or driving force within the closed dynamic system itself. There is not much controversy about the above mentioned fact. But there exist many contradictory views on the concreteness of the driving force. The author of the present work, backed by results of preliminary experiments considers that, amongst them more appropriate are those, which conclude that, the cause of chatter lies in the unstability of the machining process

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itself. Views also differ as regards the concrete type of unstability of the machining process responsible for the chatter formatton. Tailor F.B. considered that, element and segment chief formation is responsible for chatter (2). But according to others, since element and sigment chip formation occur at extremely low cutting speeds, where chatter is absent, this cannot be considered to be the right cause of chatter. Steinberg I.C. (3), Kudinov V.A. (4), Eliasberg M E. (5), and others consider that, the unstability of the built up edge induces chatter during metal cutting process. But at the same time it is well known that, most intensive chatter exists at relatively high cutting speeds, where built up edge is also absent. Doi and Kato affirmed that, metal cutting process is always accompanied by a lacking back of cutting force in phase with respect to chip thickness. Tashlitsky N.I., Shou and Holken confirmed by experimental results the above mentioned phenomenon and prepared that, this may be the cause of chatter. But the experiments of Smith, Tobias S.A. (1), Albert, Iollec, Andrew and others have affirmed that, the change of cutting force may stay back and as well as exceed in phase the change of chip thickness depending on the conditions of chip formation.

Many authors placed "regenerative force" on the basis of their theories for explaining the physical causes of chatter. But experimental results of the present work and theoretical analysis made by Eliasberg (5), show that the vibrational marks on the maching surface can not be the cause of chatter with similar frequencies if the cutting conditions are changed.

Eliasberg M E. considered that the cause of chatter is the formation of a crack above the tool point, which he observed with the help of a movie camera. But at the same time it has been established by Loladze T.N. (6), Talantov N.V. (7), Trent, and others that, at higher cutting speeds where built-up edge vanishes there can not be any space between the chip and tool, since the chip fully adheres to the tool surface. As such, the exceeding crack formation can not be accepted as the physical cause of chatter.

By the research works of the Volgograd Polytechnic Institute under the guidance of Prof. Talontov N.V. it has been earlier established that while machining high temperature strength steel and mild carbon steel (containing 0.45% C) at extremely high cutting speed the process of plastic deformation at the zone of chip formation is unstable (8).

This type of unstability leads to the so termed "cyclic chip" formation, which is very much similar to segment chip formation on external view. Cyclic, because the process of unstability is performed indefinite cycles which include two phases-phase of compression of the approaching volume of fresh metal and phase of shear in a thin revolving zone of chip formation The frequency of the unstability is determined by the temperature—deformation conditions at the zone of chip formation. With the increase of cutting speed frequency of this unstability increase continuously. But the authors of these works could not trace out the presence of this unstability at lower cutting speeds, where chatter exists, and hence could not prove that, this is the cause of chatter formation.

Another drawback of these works was the absence of any correlation of this unstability with the characteristics of the machine tool. It has been earlier established by Kudinov V.A. (4), that, metal cutting process is a part of the closed dynamic system of the machine tool and hence the study of the unstability of metal cutting process without any correlation with the characteristics of machine tool, is incomplete and is bound to be partial. But never the less, these experimental result gave a good impulse in the way to the solution of this complicated problem.

The above discussions helped to determine the aims and objectives of a research work (9), some of which may be stated as follows :

1) To find out the physical cause of chatter.

2) To determine the laws governing chatter formation, which in turn should be connected with the characteristics of both the metal cutting process and the elastic system of the machine-tool.

3) To work out effective ways of fighting chatter.

Apparatus and procedure :

To obtain the above mentioned aims the following work materials were machined : High temp strength steel-AU-481, titanium alloys-BT-6, BT-3-1 (USSR standard), carbon steele containing 0.45% and 0.20% of carbon. Machining was carried out using carbide tools of the following materials : tungsten carbides- 92% WC + 8% Co, 94%WC+ 6%Co, tungsten titanum carbides-5%TiC+85%WC +10% Co, and 15% TiC+79% WC+6%Co., carbide without tungsten-79% TiC+16%Ni+5%Mo.

The carbide tips were held mechanically on tool holders having different values of rigidity (cross section). Rigidity could as well be changed by changing the overhang.

Machining was carried out on 5 different lathe models (USSR) 1M63 and IK 62 having different values of rigidity and degrees of wear of their parts. Rigidity of different parts of the machine, tool holders for different values of its cross-section and over hang and that of the work was determined using standard methods.

Frequencies of the unstability of metal cutting process and chatter were determined parallelly by different methods : with the help of oscillo-grams of cutting load Fx, Fy, Fz, according to the pace of the vibration traces on the machining and and machine surfaces and according to the pace of teeth on the outer surface of the chip (considering chip shrinkage). Amplitude of vibration the cutting load and temperature was determined with the help of dynamometer YDM-600, amplifyer and a sensitive oscillograph. For amplifying the signal of temperature a special amplifier on the basis of an integral micro circuit was used.

Experiments carried out by following the above mentioned procedure enabled to record frequencies of the unstabilitv of metal cutting process upto 20 KHz and above to record oscillograms of cutting load Fx, Fy, Fz, temperature θ^0 upto a frequency of 2 KHz (due to the limitatations of the apparatus used). Amplitude of the relative motion of the work tool in the radial direction during chatter was determined according to the height of the waviness on the cutting surface.

Mechanism of the unstability of chip formation were studied on micro section metallographic specimens of chip roots, received by instantly stopping the cutting process at different phases of the full cycle of unstability and as well as on micro-section metallo-graphic specimens of chip. On such specimens with the help of metallographic microscopes and micro-hardness measuring instruments the grain orientation, borders of different zones and micro hardness were measured and on their basis the shear angle, length of different zones and contact areas and also the time of each phase of the cycle were determined. According to the experimental results different curves of frequency of unstability of chip formation and chatter as a function of cutting speed were drawn. It was found that, at certain ranges of cutting speeds there are parrallel existence of two and at times three and more frequencies. In Fig. 5 examples of such curves for two work materials titanium alloy and mild carbon steel (containing 0.45%C) are cited. Observations of these and many other similar curves enabled to affirm the presence of the following type of frequency versus cutting speed curves, $f=\Phi(v)$.

1. Continuously rising curves $f_{unst.}=\Phi(v)$ at a wide range of cutting speed.

2. Segments of straight lines parallel to the axis of cutting speed. In most cases two such segments were observed. They are located with respect to the continuously rising curves at higher cutting speeds. As a rule their starting point lies

on the continuously rising curves or at a point, slightly beyond this curve (towards higher C.S.).

3. Inclined, practically straight lines at certain angles to the axis of cutting speed. They may be termed as "tails" of the horizontal segments and are generally located with respect to the continuously rising curve at higher cutting speeds.

Experimental results show that, the amplitude of vibrattlon of the components of cutting force-Fx, Fy, Fz and the amplitude of vibration of work tool at frequencies corresponding to the 1st and 2nd horizontal portions of the curve f=Φ(v) have considerably high values (10). It has been

Fig. 1 a

Fig. 1. Photographs of microsection metallographic specimens of clip formed while machining titarium alloy-BT-6 at different cutting speeds—

a) Cutting speed = 0.008 M/Sec.

b) Cutting speed = 0.117 M/Sec.

also established that, an increase in the rigidity of the spindle and work system leads to the decrease of chatter frequency, defined by first horizontal portion of the curve-f=Φ(v). Frequency changes from 120 Hz to 250 Hz. An increase in the rigidity of the tool holder similarly leads to an increase of the frequency of chatter along the second horizontal portion the curve. Frequency changes from 500 Hz to 3000 Hz.

The above mentioned results enabled the confirmation of the following:

Chatter along the Ist horizontal line are the resonant vibrations of the spindle work system and the the frequency of chatter is determined by the frequency of self vibration of this system. Chatter along the 2nd horizontal line are the resonant vibrations of the tool holder, while frequency of chatter is determined by the frequency of self vibration of the same.

In the case of vibrations along the continuously rising curve funst=Φ(v). amplitude of vibration of cutting forces Fx, Fy, Fz and relative vibration of work tool in the radial direction are very little, and therefore, they may be termed as vibrations without the loss of stability of any part of the machine tool. They are caused exclusively due to the unstability of chip formation. In order to investigate whether the unstability of chip formation is a common phenomenon in metal cutting process the following experiments were carried out according to the above mentioned procedures. Work materials of three different groups titanium alloy Bt-6, high temperature strength steel IN-481 and carbon steel containing 0.45% C were machine with different tool materials under different conditions of cut.

It was observed that machining of titanium alloy is accompanied by an unstability of chip formation

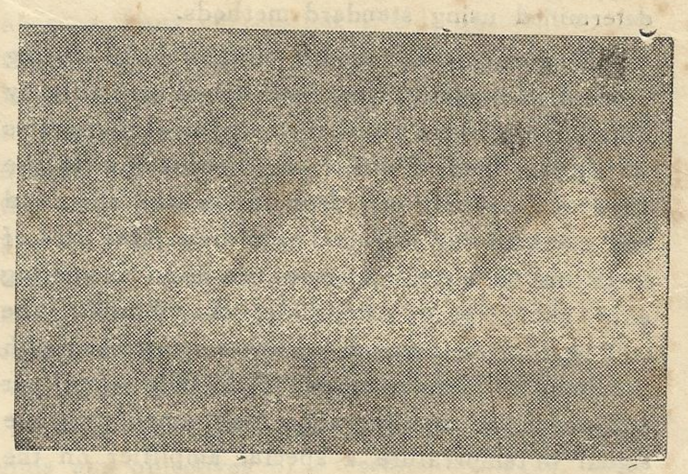

Fig. 1 b

at all cutting conditions and in the whole range of cutting speed. The frequency of the unstability follows a monotonously rising curve, Fig-5. The microsection metallographic specimens of the chips (Fig. 1,2) show that, the process of unstability is formed in definite cycles and the chip consists of teeth of definite shape and size and each tooth consists of two zones-one which is formed during the phase of shear. It should be noted that, the relative sizes of the two zones will depend on the speed at which the shear plane revolves during the phase of shear, from the position with the minimum value of the shear angle to a position with the maximum value of the same angle. As speed of deflection increases size of the zone-1 (Fig. 2) formed during the phase of shear decreases.

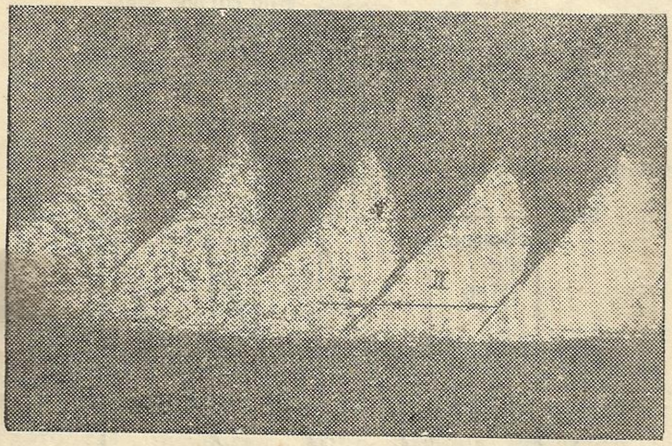

Fig. 2 a

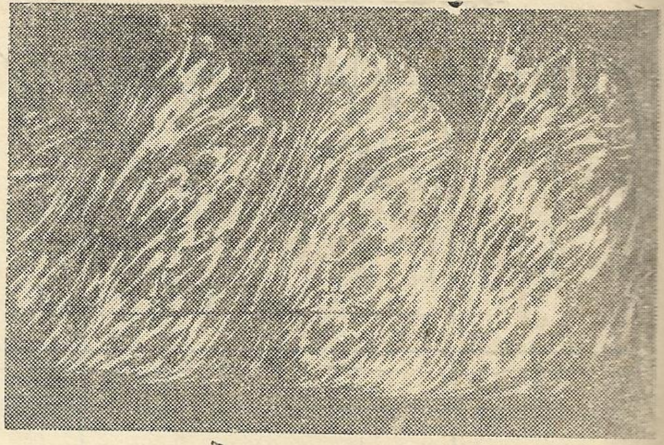

Fig. 2 b

Fig. 2. Relative sizes of the portions of chip tooth, formed during the phase of shear-I, and the phase of compression-II, for two work materia s—

a) for titanium alloy BT-6, C.S. =0.17.M/Sec.
b) for mild carbon steel containing 0.45%C, C.S. = 1.83 M/Sec.

It has been found that, speed of deflection of the shear plane increases as heat generation during the process of plastic deformation at the zone of chip formation increases and as the heat delivery from its generating areas and Debai temperature of the work material decreases.

For these reasons the above mentioned speed increases as we proceed from carbon steel with smaller value of the coefficient of heat conductivity, through high temperature strength steel, towards titanium alloys having higher value of coefficient. Size of that portion of the chip, which is formed during the phase of shear, changes in the opposite direction-decreases in the direction from carbon steel towards titanium alloys (Fig-2). These changes occur in the same direction with the rise of cutting speed, and with changes of other factors which facilitate higher heat formation and lower heat delivery from the zone of plastic deformation.

While machining titanium alloys the unstability of chip formation appears very distinctly at all cutting speeds and conditions (Fig. 1). On the other hand, the unstability of chip formation is very faint in the case of carbon steel. Moreover, at lower cutting speeds this phenomenon is very difficult to register. But especially carried out experiments have proved that, unstability is a common phenomenon in the case even carbon steel (containing 0,45% C) in the whole range of cutting speeds. This can be quite clearly observed on that side of the chip which was closer to the tool nose during chip formation. Let us number this side as I and the other as II (Fig-3a).

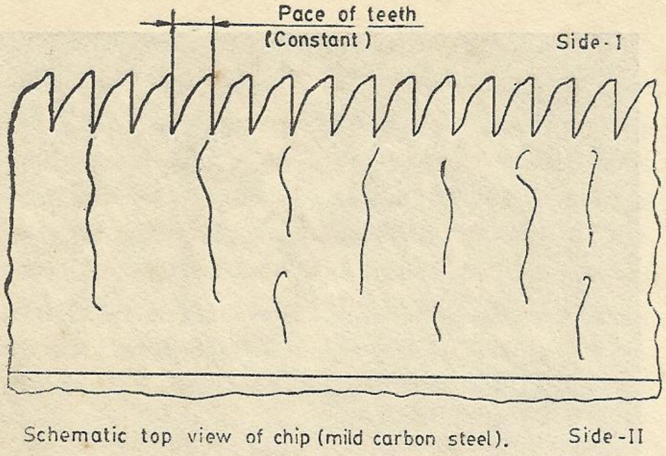

Fig. 3a

Fig. 3 Formation of small teeth on side I, of chip, formed while machining mild carbon steel (0.45%C) at different ranges of cutting speeds where—

a) chatter and intensive unstability of chip formation (u.c.f.) is absent,
b) chatter and u.c.f. exist parallelly,
c) intensive u c.f. exists alone.

A presence of continuous small teeth, paced equally, can always be observed on side I of the chip (Fig-3). These teeth can be observed at all cutting speeds. The fact that, these teeth are the result of the unstability of metal cutting process is confirmed by the following: 1. At higher cutting speeds where unstability of chip formation takes place through out the whole section of chip, pace of the teeth on side I of chip

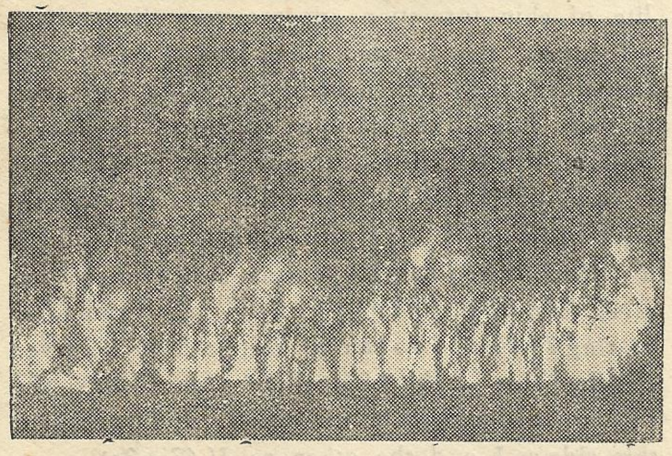

Fig. 3b

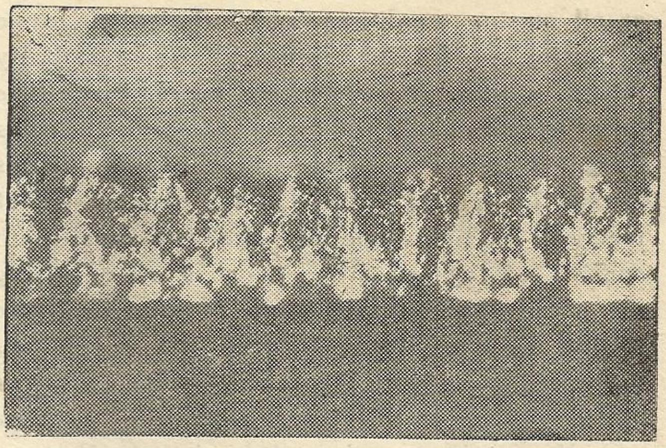

Fig. 3 c

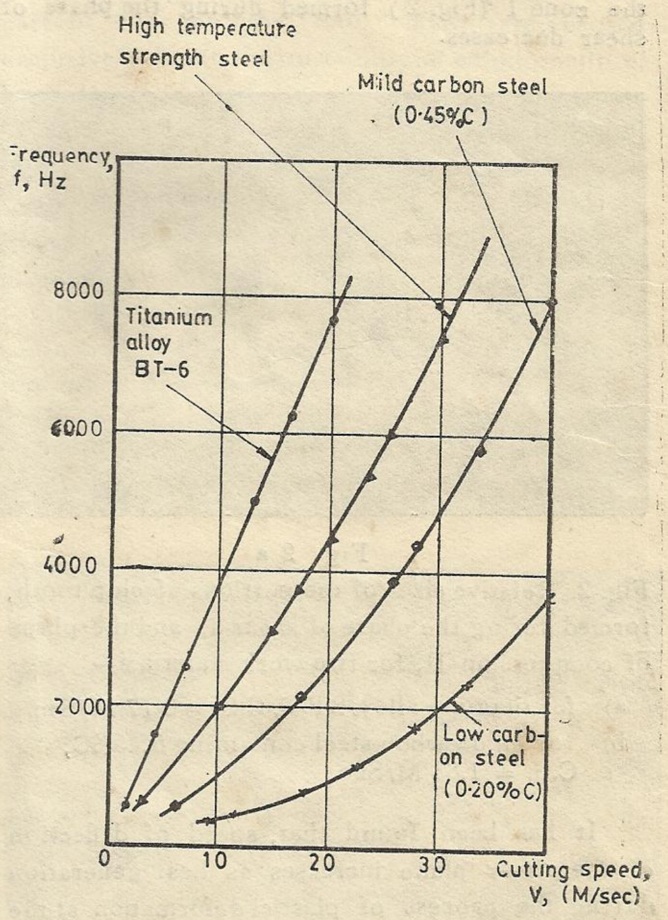

Fig. 4. Influence of work material and cutting speed on the frequency of the unstability of chip formation

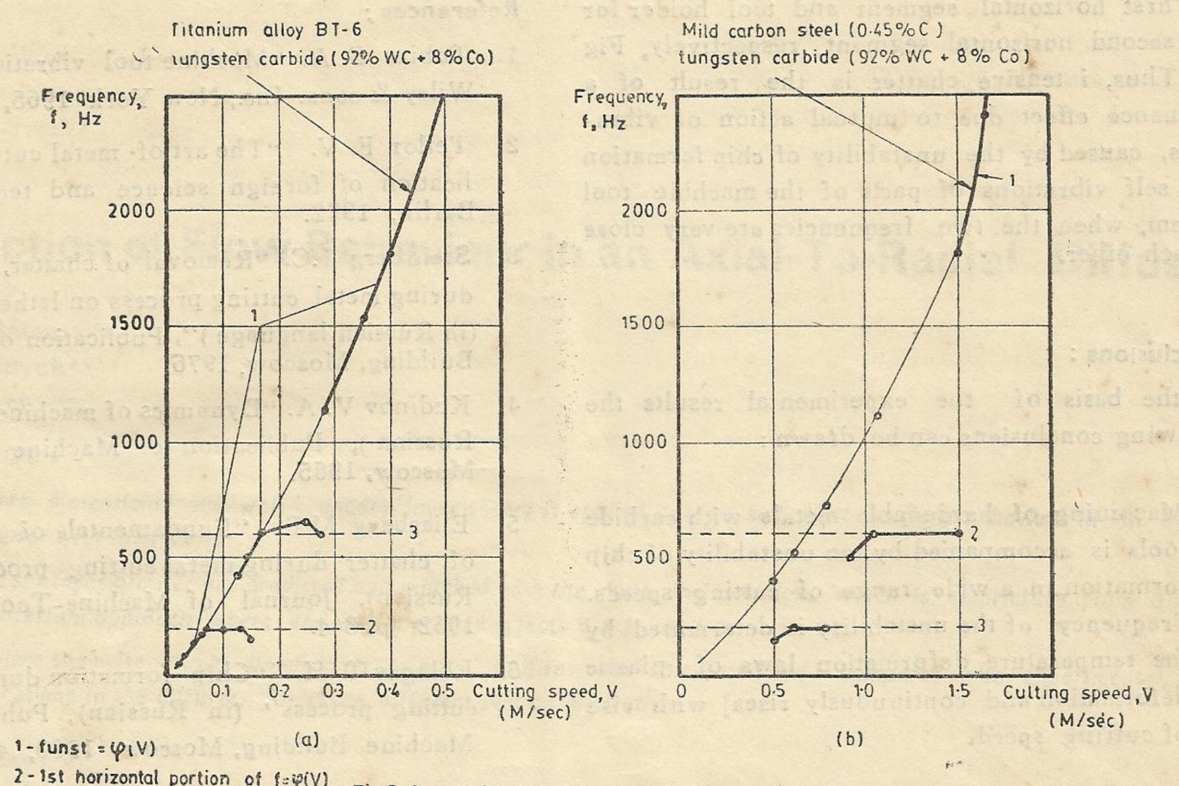

Fig.5. Laws of chatter formation during metal cutting process

completely coincide with the pace of segments through out the whole section of chip. 2. At all cutting speeds pace of the changes of micro-hardness measured along various longitudinal sections of the chip and as well as that of grain orientation fully coincides with the pace of these teeth (on side I of chip).

Results of the above mentioned experiment helped drawing the following conclusions : Unstability of chip formation is a phenomenon common to all machining operations, and appears specially while machining hardenable metals at all cutting speeds.

Continuously rising curves funst. =Φ(V) for four different materials are given in Fig-4. It is evident from the locations of the curves for different materials that, they are dictated by the temperature-de formation laws of plastic deformation. From titanium alloys, through high temperature strength steel and mild steel (containing 0 45%, C) towards low carbon steel (containing 0 2%C) these curves are gradually drifted towards higher cutting speeds.

Experimental results of the research work led to the discovery of the general mechanism of intensive chatter formation. It was earlier stated that, the frequency of such chatter are determined by segments of straight lines, parrallel to the axis of cutting speed. Location of these segments for all cases are governed by general rules : they appear at approximately cutting speeds, where the curve funst = Φ(V) coincides with straight lines, defining the frequencies of self vibrations of the spindle-work system for the first horizontal segment and tool holder for the second horizontal segment, respectively, Fig 5. Thus, intensive chatter is the result of a resonance effect due to mutual action of vibrations, caused by the unstability of chip formation and self vibrations of parts of the machine tool system, when the two frequencies are very close to each other.

Conclusions :

On the basis of the experimental results the following conclusiens can be drawn :

1. Machiuing of hardenable metals with carbide tools is accompanied by an unstability of chip formation in a wide range of cutting speeds. Frequency of the unstability is determined by the temperature deformation laws of plastic deformation and continuously rises] with rise of cutting speed.

2. Intensive chatter appears at certain ranges of cutting speeds, where vibration is caused with the loss of stability of the spindle-work system and tool bit holder. Physical cause of chatter is the unstability of chip formation. Chatter is the result of resonance effect, which is caused by mutual action of vibrations due to unstability of chip formation and potentially possible vibrations with self frequency of spindle-work system or tool bit holder, when the two frequencies are closed to each other.

3. Ranges of cutting speeds, where chatter exists depend not only on the characteristics of the elastic system of the machine-tool but also on the characteristics of the metal cutting process itself. It is possible to partially or fully eliminate chatter, verying the characteristics of machine-tool and as well as the conditions of cut.

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