TOOL WEAR UNDER DYNAMIC CUTTING CONDITIONS

by

MEHMET KAYHAN

Submitted to the Graduate School of Engineering and Natural Sciences
in partial fulfillment of
the requirements for the degree of
Master of Science

Sabancı University
August 2004

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APPROVED BY:

Associate Prof. Dr. Erhan Budak ………………………….

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DATE OF APPROVAL: ………..…………….

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…to my grandma

ACKNOWLEDGMENT

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I wish everybody that is mentioned above the very best in life.

ABSTRACT

Machining processes are very common in manufacturing technology. These operations are applied in manufacturing of almost every mechanical part. Because of their frequent use, these processes have to be efficient and economical. On the way to lower manufacturing costs, there are many parameters that engineers need to consider.

Tool wear is one of the most important considerations in machining operations as it affects surface quality and integrity, productivity, cost etc. The most commonly used model for tool life analysis is the one proposed by F.W. Taylor about a century ago. Although the extended form of this equation includes the effects of the important cutting conditions on tool wear, tool life studies have always been performed under stable cutting conditions, and the effects of chatter vibrations have never been considered.

This study presents an initial attempt to understand the tool life under vibratory cutting conditions. The wear data have been collected in turning and milling operations of mild steel and titanium alloy under many different cutting and chatter conditions. The results indicate significant reduction in tool life due to chatter as expected. Chatter results in serious reduction in tool life about 50% for most of the cases and more than 80% in some higher cutting speeds in turning. The same reduction in tool life due to chatter is about 30% in milling tests. These results can be useful in evaluating the real cost of chatter including the reduced tool life. They can also be useful in justifying the cost of chatter suppression and more rigid machining systems.

ÖZET

Talaşlı imalat, üretim teknolojisinde çok sık kullanılan bir yöntemdir. Bu işlemler imalat sırasında neredeyse tüm mekanik parçalara uygulanır. Çok yaygın kullanımlarından dolayı; talaş kaldırma işleminin verimli ve ekonomik olması gerekmektedir. Üretim mühendislerinin daha düşük imalat maliyetleri için göz önünde bulundurması gereken birçok parametre vardır.

Takım aşınması, yüzey kalitesine ve doğruluğuna, verimliliğe ve maliyete olan etkisinden dolayı; talaşlı imalatta göz önünde bulundurulması gereken en önemli kriterlerden birisidir. Takım ömrü analizlerinde en sık kullanılan modelleme, yaklaşık bir yüzyıl önce F.W. Taylor tarafından önerilmiştir. Bu denklemin geliştirilmiş şekli, takım aşınmasına etki eden birçok parametreyi içermesine rağmen; takım ömrü üzerine yapılan çalışmalar daima kararlı (titreşimsiz) kesme koşulları altında gerçekleştirilmiş ve tırlamanın etkileri göz önünde bulundurulmamıştır.

Bu çalışmada, takım ömrünü titreşimli kesme koşulları altında anlamak için yapılan ilk girişim anlatılmıştır. Takım aşınması verileri, yumuşak çeliğin ve titanyum alaşımının tornalanması ve frezelenmesi işlemlerinde birçok farklı kesme ve tırlama koşulları altında toplanmıştır. Sonuçlar beklendiği gibi, tırlamadan dolayı takım ömründe belirgin bir düşüşü göstermektedir. Tırlama tornalamada, takım ömründe; birçok durumda %50 ve bazı yüksek kesme hızlarında %80 gibi ciddi düşüşlere neden olmuştur. Takım ömründe tırlamadan dolayı oluşan azalma, frezeleme için %30 civarındadır. Bu sonuçlar, takım ömründeki azalmadan dolayı tırlamanın gerçek maliyetini değerlendirmede ve tırlama azaltılmasının maliyeti hesabında faydalı olabilir.

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CHAPTER 1

INTRODUCTION

Metal removal is the most commonly used manufacturing method to finalize the dimension, quality and shape of the mechanical parts. In many different metal removal processes, metal cutting, especially turning and milling are the most popular ones. In metal cutting processes, one of the most important and critical parameter is the tool life according to the scales of economy. The selection and wear resistance of the cutting tool determines the quality of the surface and the total cost.

Different kinds of damages can develop on the tool during the cutting process and some of these damages are called as tool wear. The amount of total tool wear and time horizon to reach the maximum limit of wear determine the tool life. Tool life is one of the critical factors in machining processes affecting cost and productivity. Many aspects of tool wear and tool life have been investigated [1,2] in last century since the legendary work of F.W. Taylor in 1907 [3]. These investigations have improved the understanding of the wear mechanism for different work and tool materials in various machining operations. They also established the foundations for improved cutting tools and increased productivity. Similar to tool wear, vibrations, particularly self-excited chatter vibrations, are very critical in machining processes. One of the conditions that accelerates the tool wear is the self-excited (chatter) vibration.

Chatter can be observed almost in every machining process, and it is common in turning and milling operations. In many cases, machining is carried out under chatter conditions either due to very low dynamic rigidity of the machining system, or in order to reduce the cycle time. Tool wear tests, on the other hand, are mainly performed under stable cutting conditions which cannot explain the wear behavior under vibratory cutting. The purpose of this work is to investigate the effects of vibrations on tool wear.

This would be an important information for understanding the wear mechanism in dynamic cutting conditions.

In addition, it would be very useful to estimate the cost of chatter due to reduced tool life in production operations. The information can also be used in justifying additional cost of rigid tooling and machine tools, and implementation of chatter suppression methods.

The effect of chatter vibration on tool life is known by experienced machinists and production engineers. The theory and mechanism of chatter vibration are commonly known but it is still a great and important difficulty in machining operations. In practice, it is known how chatter vibration reduces tool life. However there are no data or studies quantifying the effect of chatter. In this study, the effects of chatter vibrations on tool life in turning and milling are examined. Different cutting conditions are used in turning and milling tests to understand the behavior of the tool wear evolution. This is the first attempt in this area known to us.

1.1 Metal Cutting Theory

The basic idea of metal cutting is removing the undesired metal volumes by small pieces called chips by using a cutting tool which is harder than the workpiece material under a relative motion between the workpiece and the tool. The mechanics of the metal cutting processes are generally similar although geometry of the operation can be quite different. There are two general models of metal cutting: orthogonal and oblique. In orthogonal cutting, the metal is removed by a cutting edge which is perpendicular to the direction of tool-workpiece relative motion. The mechanics of oblique cutting is more complicated than the orthogonal cutting due to its three dimensional nature [4].

The modeling of the cutting process mechanics makes the predictions of the important cutting parameters possible. In orthogonal cutting, the cutting operation is assumed to be uniform along the cutting edge; therefore it is a two-dimensional plane strain deformation process without side spreading of the material [2,1]. Metal cutting operation is basically a plastic deformation process. In the cutting region, there are three main deformation zones shown in Figure 1.2. The material that is cut shears over the primary zone to become a chip as the cutting tool edge moves into the workpiece material. The newly created chip moves along the rake face of the tool which is called secondary deformation zone. Finally, the contact zone between the flank face of the cutting tool and the newly-machined surface is called the tertiary zone. In case of oblique cutting, the chip flows on the rake face in a direction which is different than the cutting speed direction defined by the chip flow angle. The shear plane, too, has an angular orientation to the cutting edge which complicates the kinematics and mechanic analysis of the process [1].

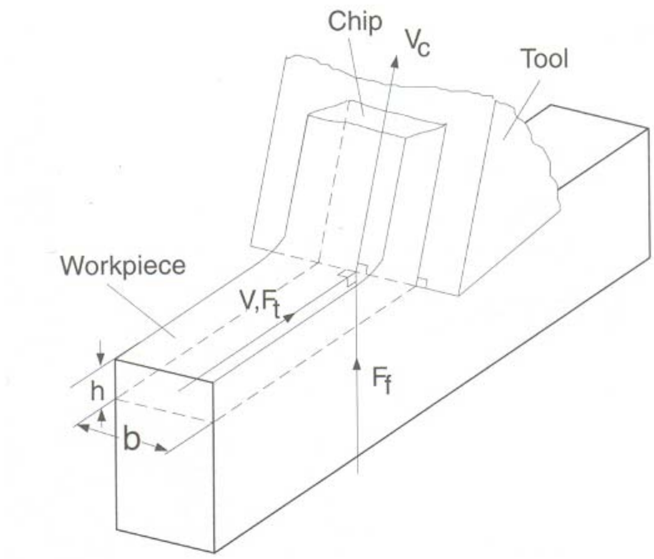


Figure 1.1: Geometry of orthogonal cutting process

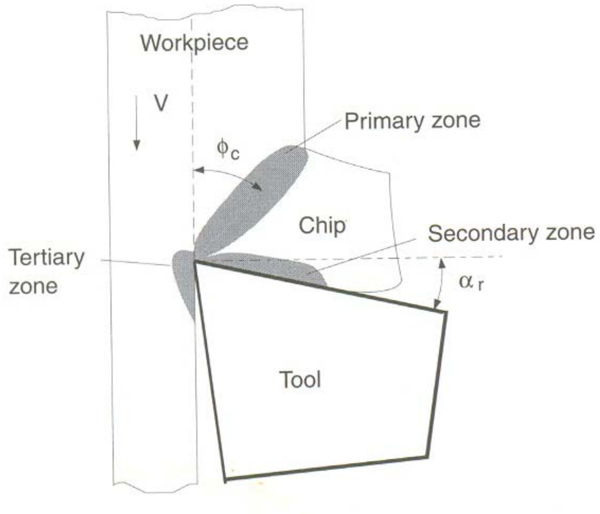


Figure 1.2: Deformation zones in cutting region

1.2 Related Literature Review

The cutting tool is one of the most important components of machining process. All major advances in machining technology depend on the advances in cutting tool materials. The most desired properties of cutting tools are high hardness at high temperatures, deformation resistance, toughness, chemical stability, adequate thermal properties, high stiffness and low cost. Today, many different cutting tool materials are used in industry such as, high speed steels (HSS), cemented carbides, cast carbides, coated cemented carbides, sintered cubic boron nitrate, polycrystalline diamond, etc. Cutting tools and tool life are vital for production costs. The life of a cutting tool is limited by the extend of wear. High temperature, high pressure, high sliding speeds and chemical reactions between cutting tool and workpiece material lead to negative mechanical and thermal shocks and fatigue on tool [5]. These effects decrease tool life.

The scientific studies about tool life have been started with the state-of-art study of F.W. Taylor in 1097 [3]. That was the first systematic tool testing study. He set a principle equation which gives the relationship between cutting speed and tool life and that equation is still valid. Many researchers [1,2] have investigated different parameters and relations of tool wear and tool life. These studies resulted with the extended Taylor tool life equation which contains more parameters to estimate tool life. Trent [6] examined various factors that affect wear of cemented tools in machining steel. Trent also suggested that the mechanism of crater wear should be different to the mechanism of flank wear. Trigger and Chao [7] investigated the crater wear of cemented carbide tools. They observed that crater wear to occur at some distance away from tool edge. Opitz and Konig [8] investigated the micro mechanisms of wear of carbide tools in machining ferrous materials. The found changes in the mechanisms of wear cutting tool with increase in cutting speed. Kramer and Suh [9] studied the mechanism controlling the crater wear of a single phase carbide cutting tools in high speed machining of steels and developed a simple model to describe the wear process. Ham, Hatomi and Thuering [10] investigated the machinability of several grades of nodular cast irons extensively to evaluate the performance of the carbide and oxide cutting tools [5].

The theory of chatter vibrations is known for a long time. The first studies [11] about self-excited vibrations have been started in the second half of the past century. Tlusty and Polacek [12] and Tobias [13] determined the most important source of self-excitation which is associated with the structural dynamics of the machine tool and the feedback between the subsequent cuts on the same cutting surface resulting in regeneration of waviness on the cutting surfaces, and thus modulation in the chip thickness [12]

Although chatter stability has been studied in detail in last half a century [12-15] chatter vibrations still continue to be one of the most important limitations in production operations. Shi and Tobias [16] showed that the boundaries of the stability increases as the feed rate increases until a nominal value. Important contributions about chatter stability came from Budak and Altintas [17] and, Jensen and Shin [18] in recent years.

Tool wear and tool life are very critical for machining processes. One of the main purposes of manufacturing engineers is to reduce tool wear and keep the tool life as long as satisfying other requirements. Chatter vibration is a cardinal adverse effect in machining and shortens tool life. There is a complex structure between tool wear, tool stiffness and chatter. Studies focused on many different aspects. The relationship between tool life and self-excited vibration has been investigated before from the view of the effect of tool wear on chatter. Tlusty [19] pointed out that the flank wear flat is critical in positive damping in the occurrence of self-excited vibrations. Chiou et al. [20] demonstrated that chatter instability is delayed to a greater overhang distance as a result of flank wear, and chatter limit increases especially at lower cutting speeds, as the tool wear increases. Chiou and Liang [21] demonstrated the effect of tool wear on chatter stability in turning. The chatter stability increases as the tool wear flat of the cutting tool enlarges.

Chiou and Liang [22] analyzed the acoustic emission in chatter vibration with tool wear effect in turning. Miyaguchi et al. [23] demonstrated that tool life increases as the cutting tool stiffness decreases in high speed milling. Clancy and Shin [24] developed a chatter prediction model including tool wear effect. They expressed the direct proportion between flank wear and stability limit, again. Fofana et al. [25] investigated machining stability in turning by using worn tool inserts. Cutting forces varying with depth of cut and feed rate and cutting force coefficients are investigated as the tool wear progresses and it is demonstrated that tool wear and dynamic instability are both contributed by the combined effect of the contact and friction mechanisms between workpiece-tool, tool-chip and workpiece-tool-machine tool interactions. Kannatey-Asibu and Lu [26] determined the effect of a worn tool on dynamics of the cutting process by investigating sound generation during surface turning and the results show that as the tool wear increases, the spectral distribution and displacement and exciting force shift.

1.3 Mechanics of Turning Process

Turning is a basic operation of metal cutting and it is the most commonly used machining process. Generally, a circular-shaped workpiece is clamped in a chuck and rotated. The cutting operation is done by a cutting tool that moves parallel to the central axis of the chuck. The cutting tool is fixed rigidly on a tool post. The geometry and the cutting forces of turning process are shown in Figure 1.3. The machine tool for the turning operations is called *the lathe*. A lathe and its components are shown in Figure 1.4.

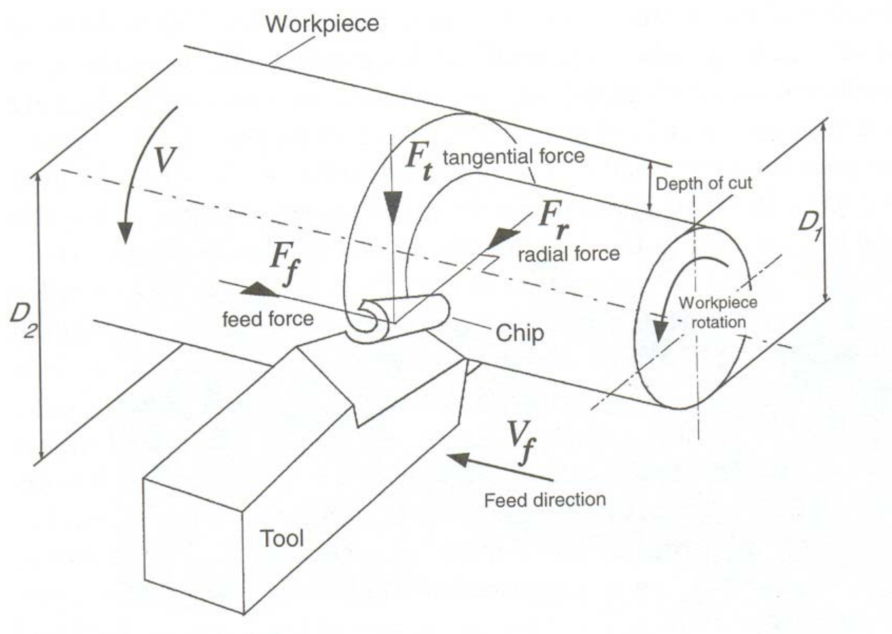


Figure 1.3: Geometry of turning process

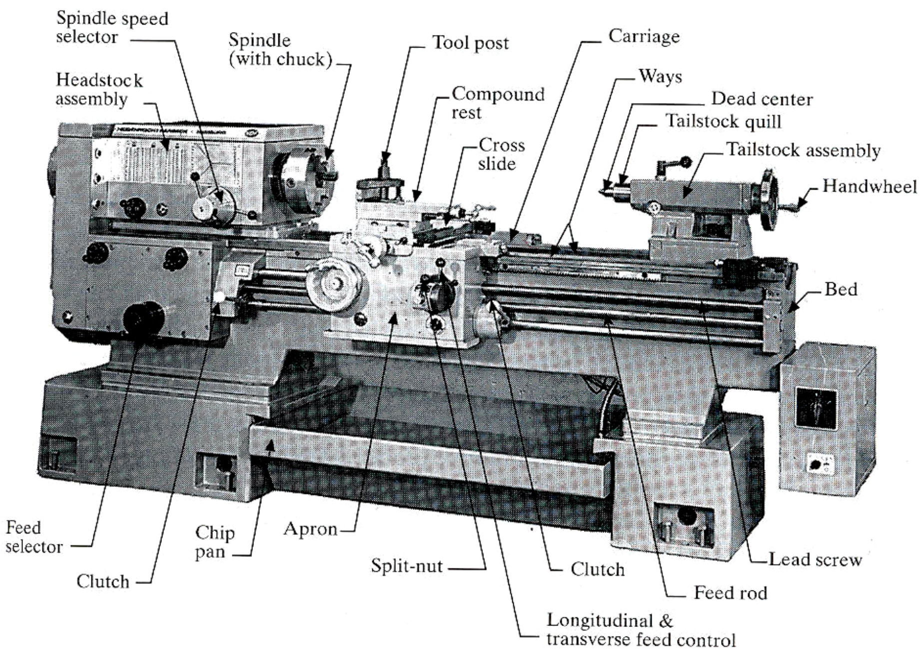


Figure 1.4: A universal lathe

The most important parameters of a turning process are the cutting speed (V), the feed rate (f) and the depth of cut. The cutting speed is the linear rate between the cutting edge of the tool and the unmachined surface of the workpiece. The feed rate is the step distance that the cutting tool moves in the axial direction in every rotation of the chuck [3].

1.4 Mechanics of Milling Process

Milling is a cutting process which is more complicated than turning. The cutting operation is done by a rotating tool that moves along various axes while the workpiece is fixed. More complex parts can be produced by milling operation [27]. The most important difference between turning and milling operations is the chip thickness generation kinematics. Every cutting tooth on a milling tool follows a trochoidal path so the thickness of the cut chip changes from the fist contact between the tooth and the material till the end of the cutting sequence of the tooth. This variability is always periodical, and can be approximated by a circular motion.

Another important difference of milling is the direction of the cutting motion. Two different models, down-milling and up-milling, can be used in a peripheral milling operation. In down-milling, cutting operation starts from the surface of the workpiece, at the point where the chip thickness is the maximum. At the end of the cutting motion of the tooth, the chip thickness decreases to zero. This kind of milling operations are recommended to prevent machining vibrations, and to obtain better surface finish. In up-milling, cutting operation starts from the minimum chip thickness and the chip thickness increases till the end of the cutting. That operation is generally used to have longer tool life.

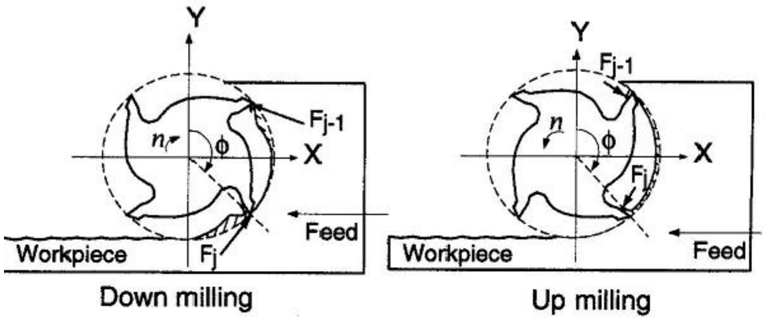


Figure 1.5: Milling modes

1.5 Tool Wear and Tool Life

Selecting the best cutting tool material for a specific application is acute in achieving efficient machining operations. The best way to increase productivity is to increase cutting speed but this option is limited due to reduced tool life. Higher cutting speeds increase the tool wear so tool regrinding or replacement costs, and interruptions in the process are increased [1]. The change of shape of the tool from its original shape, during cutting, resulting from the gradual loss of tool material is called tool wear [28].

Cutting tools are exposed to extremely severe rubbing processes. The tools are in metal-to-metal contact, between the chip and workpiece, under very high stress levels at high temperatures. During the cutting process, cutting tools remove the metal from the workpiece to achieve the required shape, dimension and surface finish quality. However, tool wear occurs during the cutting sequence, and it results in the failure of the cutting tool. When the tool wear reaches a specific limit , the tool or the removable insert has to be replaced with a new one to guarantee the ordinary cutting action [38]. Several different wear types occur during the cutting process. The most important types are crater wear, flank wear and notch wear. These are shown in Figure 1.6.

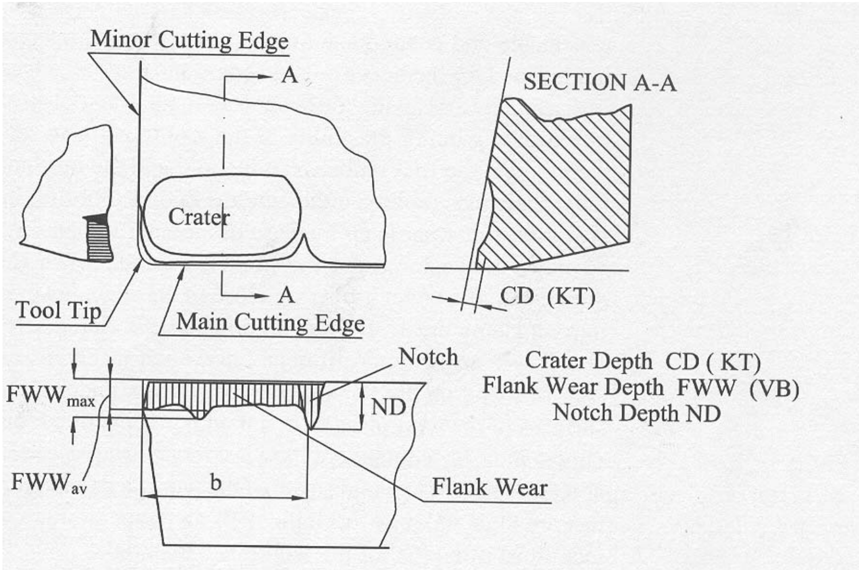


Figure 1.6: Tool wear parameters

The chip flows away on the rake face of the tool and that motion results in a severe friction between the chip and the rake face. So, it leaves a scar on the rake face which is parallel to the major cutting edge. That damage on the rake face of the tool is called crater wear.

The flank wear land generally develops due to abrasion of the cutting tool edge against the machined workpiece surface. Flank wear is measured by the average and maximum width of wear land size and denoted as VB and $VB_{\max}$,respectively.

The notch wear is a combination of flank and rake face wears which occurs on the primary clearance face, adjacent to the depth of cut line where the major cutting edge intersects the workpiece surface. It generally accelerates more rapidly than the flank wear.

Flank wear size is generally used as a the tool life criterion. The development of flank wear can be split into three zones in the tool life curve [see Figure 1.7]. A quick and rapid wear section at the beginning of the cutting operation, a stable rate development on the amount of the wear zone directly proportional to the machining time and finally, a high acceleration in the flank wear after reaching the wear limit. The cutting time that corresponds to that wear limit is called tool life.

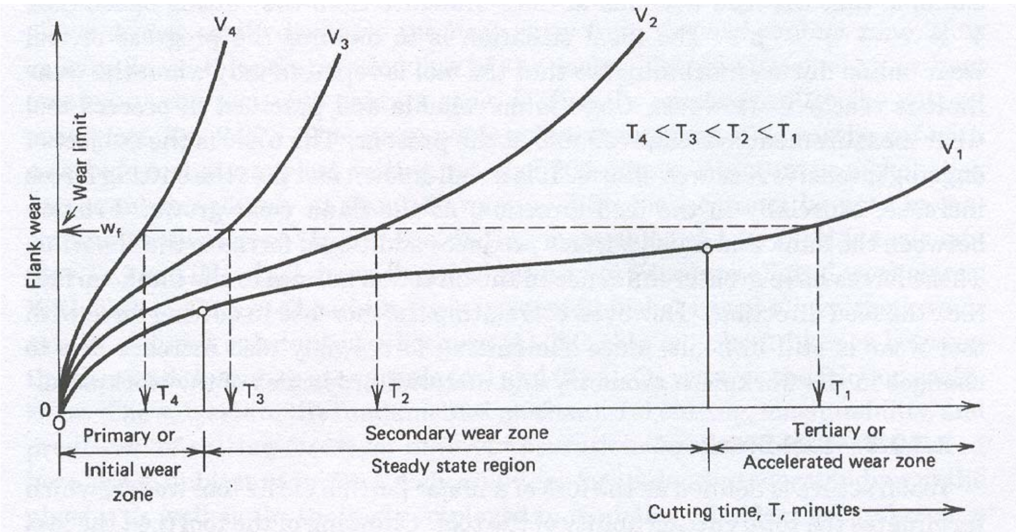


Figure 1.7: Taylor's tool life curves

The scientific studies about tool life were started with the pioneering state-of-the-art work of F.W. Taylor with the title *On the Art of Cutting Metals* in 1907 [3]. Many researchers studied the issue for many years after that paper. The relation between the cutting speed and the tool life was first investigated by Taylor who expressed this relation in the following form

$$VT^n = C' \tag{1.1}$$

where V [m/min] is the cutting speed, T [min] is the tool life and C and n are experimentally identified constants which depend on work and tool material.

The effects of other cutting conditions, i.e. chip thickness and depth of cut, were neglected in the elementary tool life equation. Their effects on the tool life can be included in the extended tool life equation [30]

$$VT^n d^x f^y = C \tag{1.2}$$

and from that equation:

$$T = \frac{C}{V^{\frac{1}{n}} d^{\frac{x}{n}} f^{\frac{y}{n}}} \tag{1.3}$$

where f [mm/min] is the feed rate, d [mm] is the depth of cut, C, x and y are experimentally identified constants similar to the ones in Eq. 1.1. The effect of vibration on tool wear has never been considered in the previous studies on tool life, although it is common knowledge that the wear rate under dynamic conditions are higher, and thus the resulting tool life is usually much shorter than the ones predicted by Eq. 1.1 or 1.2.

The tool wear affects some parameters of the cutting process and vice versa. These parameters are cutting forces, surface finish, dimensional accuracy and machining vibrations. The tool wear increases the cutting forces. The wear zones on the clearance face of the tool further increase the cutting forces due to increased rubbing force between tool and the surface of the workpiece. One exception to that is, the crater wear in which case the wear may decrease the cutting forces because of the increased rake angle due to the crater. The surface finish after the machining process becomes poorer as the tool wears out. This is a generalization, and there may be some exceptional cases. For example, the surface finish of a cutting tool which is worn very little leaves a better surface quality according to a brand new cutting tool. As the initial rough edge coming from the manufacturing of the tool is improved due to the wear. Flank wear can also influence the original geometry of the cutting tool and thus affects the dimensional accuracy of the workpiece [1].

1.6 Chatter Vibration

There are several types of vibrations which may arise in machining processes. Compared to free and forced vibrations, self excited chatter vibrations are much more detrimental to finished surfaces and cutting tools due to their unstable behavior which may result in large amplitude relative displacements between the cutter and workpiece. Self-excited vibrations, or chatter, develop at one of the natural modes of the cutting system including tool, workpiece, machine tool, fixture etc. as a result of dynamic interaction between the structure and the cutting process in machining operations.

Under vibrations, the chip thickness becomes modulated which in turn creates dynamic cutting forces at a frequency close to one of the natural modes, and further excites the system. Under these conditions, if the vibration amplitude does not reduce and diminish compared to the amplitude in the previous pass, the amplitude of the vibrations grow continuously resulting instability, namely self-excited (chatter) vibrations. The fundamental mechanism of chatter has been investigated and analyzed starting with Tobias and Tlusty [11,12] for the last 50 years. Since then, many models have been developed for analysis of chatter vibration and prediction of chatter stability limits for different machining processes [31-33].

The chatter research has shown that the depth of cut (chip width) is the most critical factor affecting the stability of the cutting process [34]. The cutting process is more stable when the depth of cut is smaller. Chatter vibration is started by the increase of the depth of cut after the chatter limit point (b_{lim}), and becomes more pronounced at higher depth of cuts. It is very clear that b_{lim} is the most important parameter for stability in cutting. The value of b_{lim} depends on the dynamic characteristics of the machine tool, workpiece material, cutting speed and geometry of the tool [27].

1.6.1 Chatter Vibrations in Turning

The dynamics of self-excited vibration in turning is not as complicated as milling. There are two main sources of chatter in machining. These are mode coupling and regeneration of waviness. Mode coupling occurs due to cutting tool vibrations in both, x and y directions which creates a net energy input into the process under certain conditions. Regeneration of the waviness is the result of modulated chip thickness due to tool vibrations in the successive passes from the same surface location. In almost all cutting processes, the tool removes the material on the surface which was left by the previous pass, and there will be a waviness on the surface if there is any vibration between the cutting tool and the workpiece. That waviness changes the chip thickness in the next pass (the next revolution in turning and the next tooth in milling). The cutting tool encounters a wavy surface and removes the chip with periodically varying thickness which creates wavy surface for the next pass. So the waviness is continuously regenerated [27].

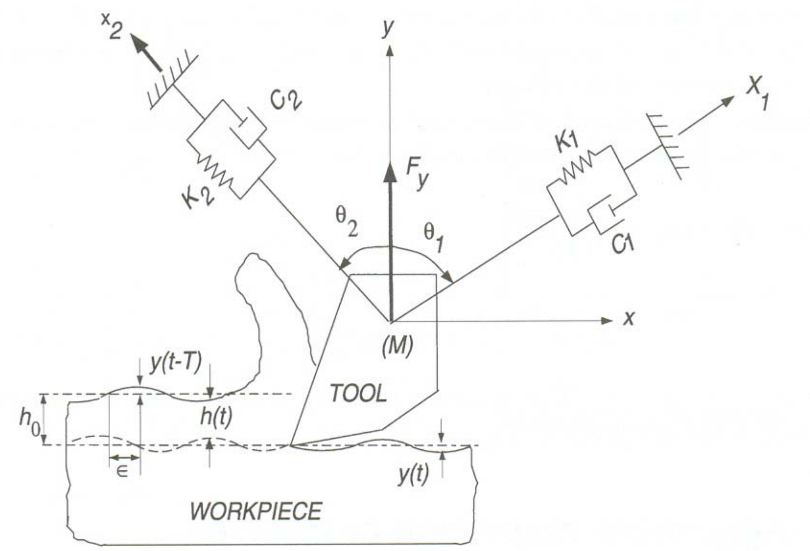


Figure 1.8: Chatter model for turning

The chatter process is a close-loop in which force variations are created by the vibrations and visa-versa. The cutting force depends on vibrations in two subsequent passes defined by the following equation.

$$F = K_f bh \tag{1.4}$$

where K_f is the cutting force coefficient in the feed direction, b is the width of chip and h is the chip thickness. But h is the total value of h_m which is the mean chip thickness and the difference between the undulation of the surface from the previous pass, Y_0, and vibrations in the present pass Y

$$h = h_m + (Y_0 - Y)e^{j\varpi t} \tag{1.5}$$

The cutting force has two components, a mean part and a variable part. The mean component of the cutting force, F_m, can be neglected if the system is considered as linear. So the cutting force equation can be written as follows

$$F = K_s b(Y_0 - Y) \tag{1.6}$$

where $(Y_0 - Y)$ is the variation of chip thickness. The dynamic displacements can be expressed as

$$Y = FG(\varpi) \tag{1.7}$$

where $G(\omega)$ is the oriented transfer function of the system. $G(\omega)$ is the ratio between the complex amplitude of the Y component of all the vibrations in the Y direction over the complex amplitude of the force and that ratio is a function of the frequency, ω. The sum of all the direct transfer functions G_i multiplied by the directional factors u_i gives the oriented transfer function as

$$G = \sum_{1}^{i} u_i G_i \tag{1.8}$$

where

$$u_i = \cos\alpha_i \cos(\alpha_i - \beta) \tag{1.9}$$

To eliminate the force component from the equation, Eqs. 1.6 and 1.7 are combined as

$$Y = K_s bG(Y_0 - Y) \tag{1.10}$$

After this modification

$$\frac{Y_0}{Y}=\frac{\frac{1}{(K_s b)}+G}{G} \tag{1.11}$$

The vibrations are accepted as long as there is no increase occur from pass to pass process, so the magnitudes of $|Y_0|$ and $|Y|$ are

$$\left|\frac{Y_0}{Y}\right|=1 \tag{1.12}$$

which indicates marginal stability or chatter stability limit. Combining the Eqs. (1.11) and (1.12), the following is obtained

$$\left|\frac{1}{K_s b}+G\right|=|G| \tag{1.13}$$

where the equality of the absolute values of two complex numbers is expressed. There are two parts in this condition

$$\mathrm{Im}(G)=\mathrm{Im}(G)$$

which is very clear, and

$$\frac{1}{K_s b}+\mathrm{Re}(G)=\pm\,\mathrm{Re}(G)$$

where the + sign leads to $b=\infty$, and the sign $-$ leads

$$\frac{1}{K_s b}=-2\,\mathrm{Re}(G) \tag{1.14}$$

where the actual condition for the stability limit is expressed. So the limit of the width of chip for a stable cutting in orthogonal turning operations can be written as

$$b_{\lim}=\frac{-1}{2K_s\ \mathrm{Re}(G)_{\min}} \tag{1.15}$$

1.6.2 Chatter Vibrations in Milling

The variable and rotating cutting force and chip thickness direction and discrete cutting periods make the chatter theory in milling more complicated. Milling cutters can be considered to have two orthogonal degrees of freedom as shown in Figure 1.9 [4].

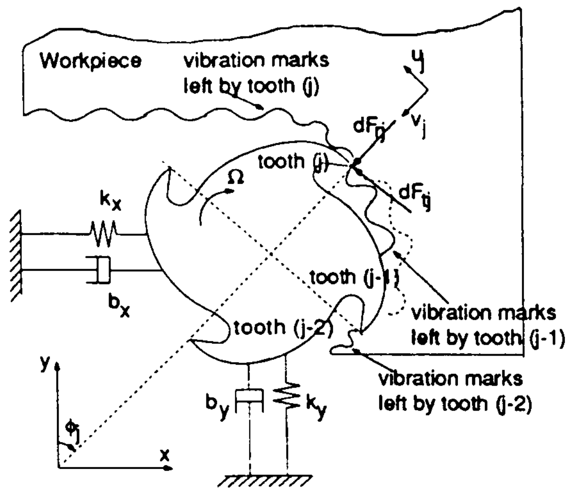


Figure 1.9: Chatter model for milling

The forces appear during cutting process excite the structure, cutting tool and workpiece, and that external coerce causes dynamic vibrations. These vibrations are imprinted on the surface of the workpiece. Every tooth removes material from the wavy surface left from the previous tooth and that situation leads to modulated chip thickness, which can be written as follows

$$h_j(\phi) = (v^o_{j_c} - v^o_{j_w}) - (v_{j_c} - v_{j_w}) + f_t \sin\phi_j \tag{1.16}$$

where $\phi=\Omega t$ is the angular position of the cutter measured with respect to the first tooth and corresponding to the rotational speed Ω (rad/sec), v_j's and v_j^o's are the dynamic displacements due to cutting tool and workpiece vibrations for the present and previous tooth periods and f_t is the feed rate per tooth. In Eq. 1.16, c and w indicate cutting tool and workpiece, respectively. The static component of the equation is disregarded in the stability analysis.

Then the dynamic chip thickness can be expressed by

$$h_j(\phi) = \lfloor \Delta x \sin\phi_j + \Delta y \cos\phi_j \rfloor \tag{1.17}$$

where

$$\Delta x = (x_c - x_c^o) - (x_w - x_w^o)$$
$$\Delta y = (y_c - y_c^o) - (y_w - y_w^o)$$

where (x_c, y_c) and (x_w, y_w) are the dynamic displacements of the cutting tool and workpiece in x and y directions, respectively. Similar to static force analysis, total dynamic milling forces on the cutting tool can be obtained using the dynamic chip thickness as

$$\begin{Bmatrix} F_x \\ F_y \end{Bmatrix} = \frac{1}{2} a K_t \begin{bmatrix} a_{xx} & a_{xy} \\ a_{yx} & a_{yy} \end{bmatrix} \begin{Bmatrix} \Delta x \\ \Delta y \end{Bmatrix} \tag{1.18}$$

where the directional dynamic milling coefficients are given in [4].

Considering that the angular position of the parameters depends on angular velocity and time, Eq. 1.18 can be expressed as

$$\{F(t)\} = \frac{1}{2} a K_t [A(t)] \{\Delta(t)\} \tag{1.19}$$

As the cutting tool rotates, the direction factors vary with time and that is the fundamental difference between milling and turning. $[A(t)]$ is periodic at the tooth passing frequency $\omega = N\Omega$ or corresponding tooth period of $T = 2\pi/\omega$. Fourier series expansion of periodic term can be used for solution of the periodic systems. As the $[A_0]$, directional coefficient, is valid between entry and exit immersion angles of the cutting tooth (ϕ_{st} and ϕ_{ex}):

$$[A_0] = \frac{1}{\phi_p} \int_{\phi_{st}}^{\phi_{ex}} [A(\phi)] d\phi = \frac{N}{2\pi} \begin{bmatrix} \alpha_{xx} & \alpha_{xy} \\ \alpha_{yx} & \alpha_{yy} \end{bmatrix} \tag{1.20}$$

where

$$
\begin{aligned}
\alpha_{xx} &= \frac{1}{2}\left[\cos 2\phi - 2K_r\phi + K_r \sin 2\phi\right]_{\phi_{st}}^{\phi_{ex}} \\
\alpha_{xy} &= \frac{1}{2}\left[-\sin 2\phi - 2\phi + K_r \cos 2\phi\right]_{\phi_{st}}^{\phi_{ex}} \\
\alpha_{yx} &= \frac{1}{2}\left[-\sin 2\phi + 2\phi + K_r \cos 2\phi\right]_{\phi_{st}}^{\phi_{ex}} \\
\alpha_{yy} &= \frac{1}{2}\left[-\cos 2\phi - 2K_r\phi - K_r \sin 2\phi\right]_{\phi_{st}}^{\phi_{ex}}
\end{aligned}
\tag{1.21}
$$

Then, the single frequency solution takes the form in the following as

$$\det\left[\left[I\right] + \Lambda\left[G_0(i\omega_c)\right]\right] = 0 \tag{1.22}$$

where $[I]$ is the unit matrix, and the oriented transfer function matrix is expressed as

$$
\begin{aligned}
&\left[G_0\right] = \left[A_0\right]\left[G\right] \\
&\left[G(i\omega_c)\right] = \left[G_c(i\omega_c)\right] + \left[G_w(i\omega_c)\right] \\
&\left[G_p\right] = \begin{bmatrix} G_{p_{xx}} & G_{p_{xy}} \\ G_{p_{yx}} & G_{p_{yy}} \end{bmatrix} \qquad (p = c, w)
\end{aligned}
\tag{1.23}
$$

and the eigenvalue of the equation 1.22 can be regarded as

$$\Lambda = -\frac{N}{4\pi} K_t a\left(1 - e^{-i\omega_c T}\right) \tag{1.24}$$

The stability limit can easily be found by using the eigenvalue in Eq. 1.24 and also the eigenvalue can be solved for a given chatter frequency, w_c. The eigenvalue can be computed from Eq. 1.22 numerically. However, the cross transfer functions in Eq. 1.22, G_{xy} and G_{yx}, must be neglected to make an analytical solution possible

$$\Lambda = -\frac{1}{2a_0}\left(a_1 \pm \sqrt{a_1^2 - 4a_0}\right) \tag{1.25}$$

where

$$
\begin{aligned}
a_0 &= G_{xx}(i\omega_c) G_{yy}(i\omega_c)\left(\alpha_{xx}\alpha_{yy} - \alpha_{xy}\alpha_{yx}\right) \\
a_1 &= \alpha_{xx} G_{xx}(i\omega_c) + \alpha_{yy} G_{yy}(i\omega_c)
\end{aligned}
\tag{1.26}
$$

Since the transfer functions are complex, the eigenvalue will has real and imaginary parts. The axial depth of cut (a) is a real number. When $\Lambda=\Lambda_R+i\Lambda_I$ and $e^{-i\omega cT}=\cos\omega_c T - i\sin\omega_c T$ are substituted in Eq. 1.25, the imaginary part of the equation vanishes

$$\kappa=\frac{\Lambda_I}{\Lambda_R}=\frac{\sin\omega_c T}{1-\cos\omega_c T} \tag{1.27}$$

A relation between the chatter frequency and the spindle speed can be obtained in order to solve the equations above [33]

$$\begin{aligned} &\omega_c T=\varepsilon+2k\pi \\ &\varepsilon=\pi-2\psi\ ;\ \psi=\tan^{-1}\kappa \\ &n=\frac{60}{NT} \end{aligned} \tag{1.28}$$

where ε is the phase difference between the inner and outer modulations ($\varepsilon < 2\pi$), k is the largest possible integer corresponding to the number of vibration waves within a tooth period, and n is the spindle speed. After the imaginary part in Eq. 1.25 is vanished, the stability limit for chatter-free axial depth of cut is obtained as [34]

$$a_{\lim}=-\frac{2\pi\Lambda_R}{NK_t}\left(1+\kappa^2\right) \tag{1.29}$$

The stability limit and corresponding spindle speed can be determined by the Eq. 1.28 and 1.29. The stability lobe diagram [see Figure 1.10] can be obtained if these calculations are repeated for a range of chatter frequencies and number of vibration waves, k.

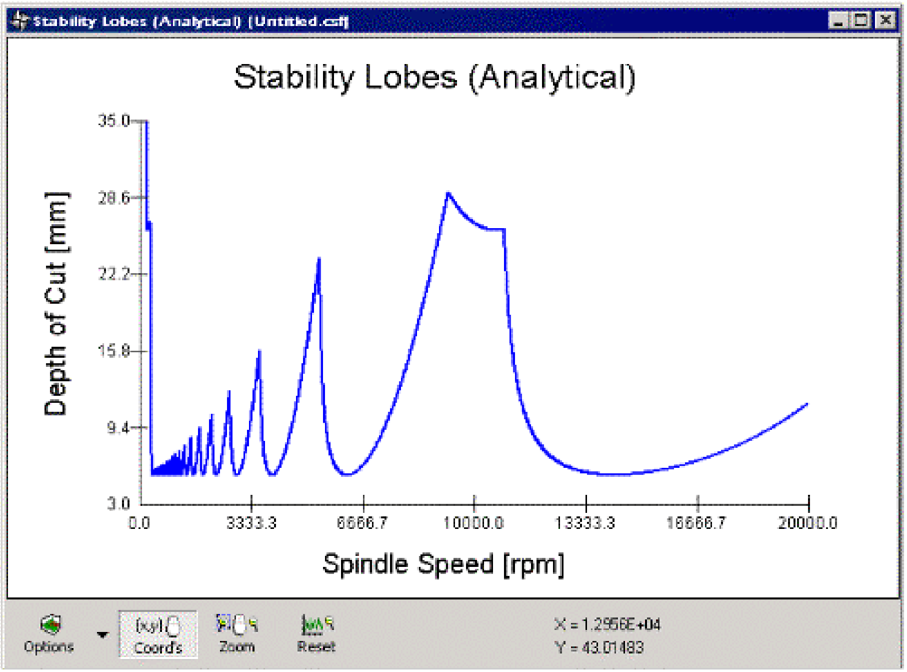


Figure 1.10: Stability lobe diagram for milling

1.7 Scope of the Study

Due to its wide use and importance in industry, cutting tools and tool life are considered. The main concern of this master thesis is to define the relationship between tool life and self-excited vibrations. The study is focused on experimental work due to insufficient information in the literature and its conundrum state as analytically. So the thesis is based on the cutting tests and their results.

There are many topics which are directly related with the study like tool wear and tool life, chatter and its modeling, mechanics of the test processes etc. These issues are explained in Chapter 1.

The results are obtained after many hours of cutting tests and their pre-studies. Chapter 2 goes into details of the test procedure. The experiments to predict the chatter stability limits, frontier tests to find the right cutting conditions, methodology of the cutting tests and properties of the equipments which are used during and after the experimental work are told in Chapter 2.

In chapter 3, the results are presented. Tool wear data for every different cutting conditions and parameters, vibration amplitudes, all cutting forces, graphs which are related to the results and, detailed inspections of the cutting tools after the tests which are obtained during the experimental sequence are analyzed and discussed.

The discussion of the experimental results which are obtained during the cutting tests are provided in Chapter 4. The results and their reasons are explained and investigated in this chapter.

The conclusions of the study and cutting tests, and future works are presented in chapter 5.

CHAPTER 2

METHODOLOGY

In this study, the effects of self-excited vibrations on tool life have been investigated. The tests are applied in a wide-range of conditions in order to have better and various data about the characteristic of the wear process under chatter. Tool wear, cutting forces, vibration amplitudes and surface roughness are inspected during the cutting tests. Many analysis and measurements are also performed before the cutting tests.

First of all, the cutting tests are performed in two different machining processes, turning and milling. These two are the most common metal cutting operations in manufacturing technology, and the data about these processes would be more useful for the industry. Different chatter intensities are imposed on the system to see the effect of the magnitude of self-excited vibrations in turning. These two vibration magnitudes are mild chatter which is undesired and severe chatter which is extremely unacceptable in every kind of machining operation. Different cutting speeds are used to clarify the effect of speed under dynamic cutting conditions and different tool lengths are used to observe the effect of different tool frequencies and stiffness on tool life. And also, some of these tests are applied for different workpiece materials in order to clarify the results for different materials.

2.1 Dynamic Conditions

Different depth of cuts over the chatter limit are used in cutting tests. By this way, different kinds of chatter vibrations are imposed on the cutting process and the outputs lead to understand the effect of different chatter intensities on tool life. The minimum chatter limit ($b_{critical}$) is the minimum depth of cut which is the intersection line between the lower bound of unstable region and the upper bound of stable (chatter-free) region. In turning and milling, any depth of cut higher than the minimum chatter limit leads to self-excited vibrations. A stability lobe diagram is shown in Figure 2.1.

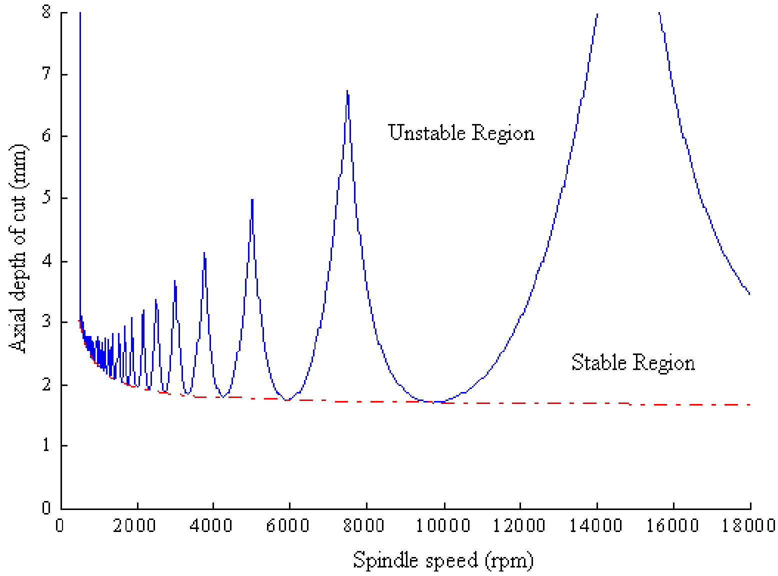


Figure 2.1: Stability lobe diagram

The chatter limit depends on many parameters such as, machining parameters (cutting speed, feed rate, up or down milling), cutting tool parameters (stiffness, frequency, damping ratio, material, geometry), workpiece material etc. A method called modal analysis is used to obtain the chatter limit and the stability diagram. Some measurements have to be done and then the system parameters must be identified using modal analysis.

2.1.1 Modal Testing and Analysis

Modal frequencies, mode shapes and system parameters (damping ratio, equivalent mass and stiffness) are required to define the dynamics of the machine tools. Experimental modal analysis (impact test) is an advanced method that is used to measure the response of a machine tool or any other structure. The outputs of the modal test are used to identify some of the dynamic properties. Acceleration, displacement or velocity sensors can be used to measure the response of the structure and the resulting vibrations, while usually an instrumented hammer is used to generate the impulse force.

The mode shapes, natural frequencies and system parameters are determined by using the frequency response function (FRF). First of all, the frequency response functions are determined by impact test and then they are analyzed. The input (impact load) is applied by using the hammer at the different points of the structure. The response against this load is measured by an accelerometer at only one point. Testing the functional transfer and transactional characteristics of a mechanical structure involve mounting the accelerometer at one location of interest and applying the impact to the object with the hammer at that point or some other point. The frequency response measurement of a structure is shown in Figure 2.2.

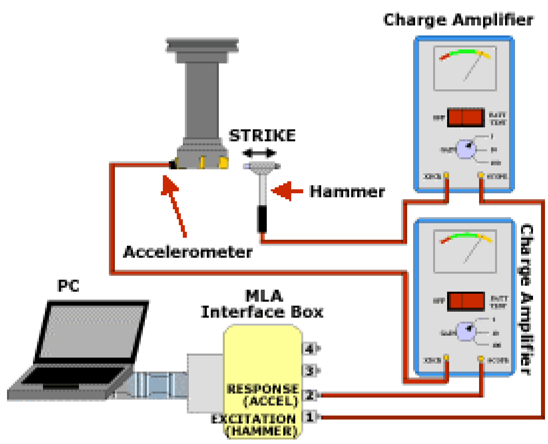


Figure 2.2: Measurement of transfer function

The impact hammer contains a quartz force sensor mounted on the striking tip of the hammer head. That quartz force sensor is used to transfer impact force into electrical signal for display and analysis. Signals generated by impact hammer and accelerometer are extended by the amplifiers. These sensors are commonly used since they are easy to use and interface with data recording and acquisition instruments for collection and analysis of the data. But the mass of the impact hammer and the size of the accelerometer must be selected properly according to the mass and rigidity of the structure being excited.

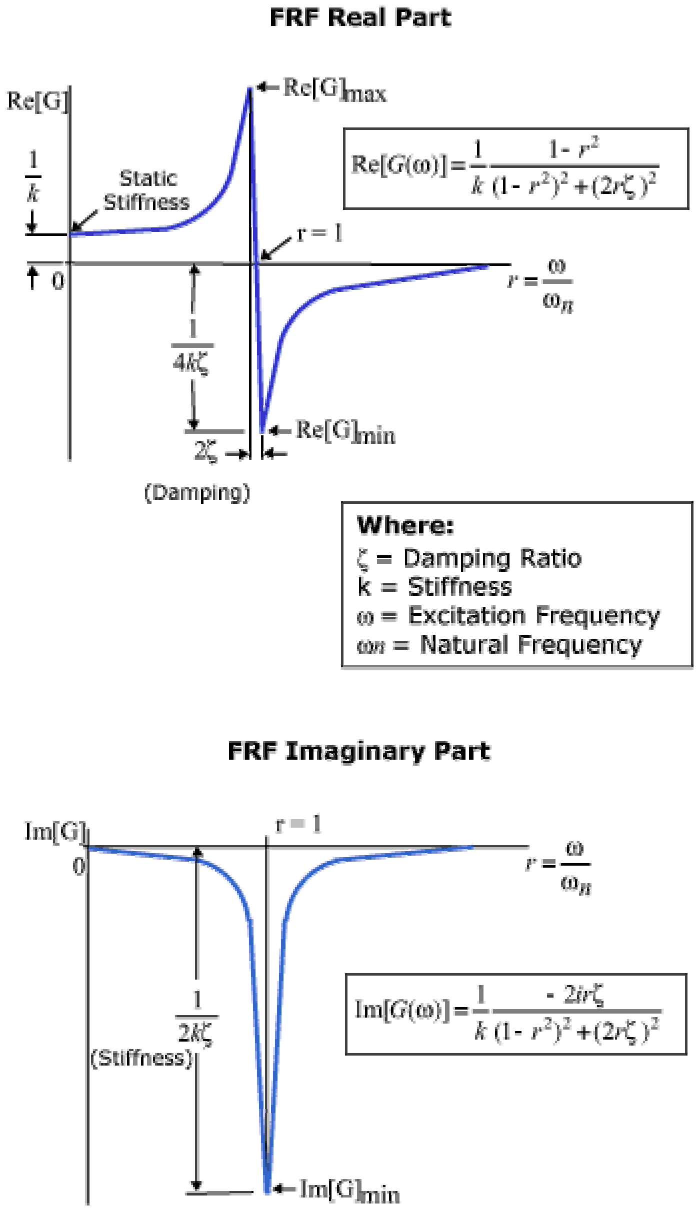


Figure 2.3: Real and Imaginary parts of an FRF

In Figure 2.3, plots of an FRF are shown. The FRF indicates the dynamic characteristics of a structure and indicating the damping ratio and the natural frequency.

Time response of the accelerometer is measured, but the same data must be converted into frequency domain. Fast Fourier Transform (FFT) is used to convert the time data. Computers can be used to collect to the data, estimate the modal parameters and display the results. A portable computer is used in all the steps of the modal analysis. All the data is collected by the software CutPro® MalTF and the modal analysis is performed by the software CutPro® Modal [4,35].

2.1.2 Determining Stability Limit Procedure in Turning

Determining the stability limit in turning process is less complex than the milling process. The unknown values in the Eq. 1.15 have to be found in order to predict the minimum stability limit. These unknowns are K_s and $Re(G)_{min}$.

K_s is the cutting coefficient in the feed direction which is parallel to the workpiece axis. That parameter is a function of the cutting force in the feed direction, depth of cut and feed rate and it varies for every material. Several cutting tests are applied to obtain an acceptable cutting coefficient for the test material, AISI 1040 steel.

$$K_s = \frac{F_s}{bh} \tag{2.1}$$

In these cutting tests, the feed rate is increased in a wide range between 0.08 mm/rev and 0.45 mm/rev. The cutting forces are measured for every feed rate in every test. The other cutting parameters are kept constant during the tests. The cutting speed is 150 m/min and the depth of cut is 0.45 mm. The following cutting coefficients are obtained after the pre-tests.

Feed rate (mm/rev)	K_t (N/mm^2)	K_s (N/mm^2)	K_r (N/mm^2)
0.08	3722	2194	1889
0.11	3232	1717	1616
0.12	3333	1667	1481
0.20	3055	1444	1444
0.24	2851	1250	1453
0.28	2753	1080	1278
0.32	2604	951	1222
0.45	2333	678	1033

Table 2.1: The cutting coefficients

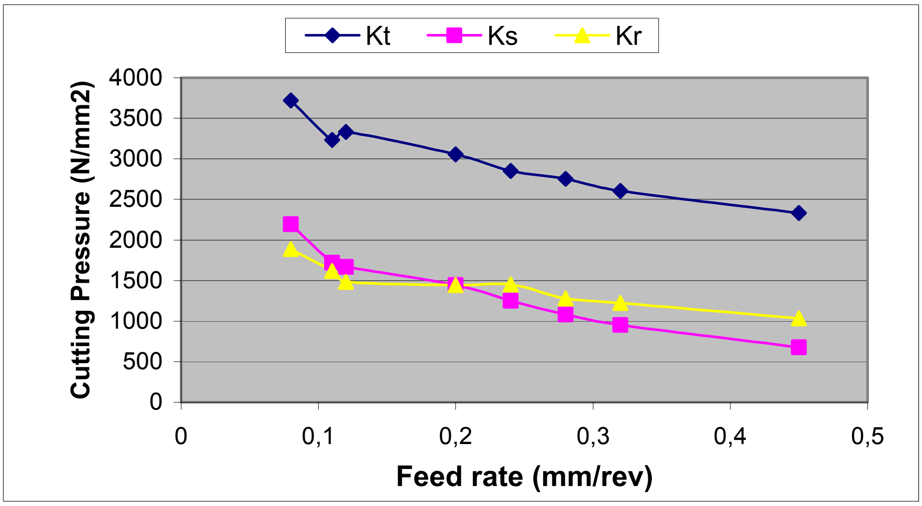
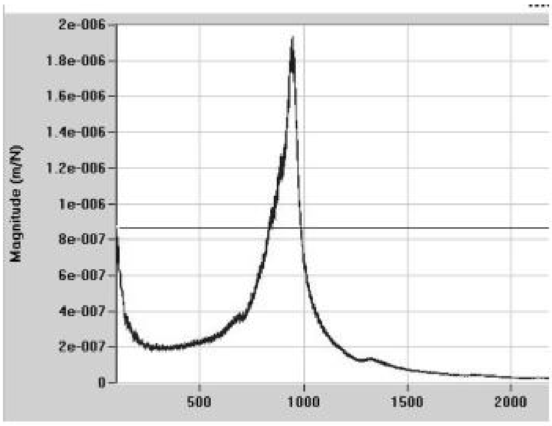


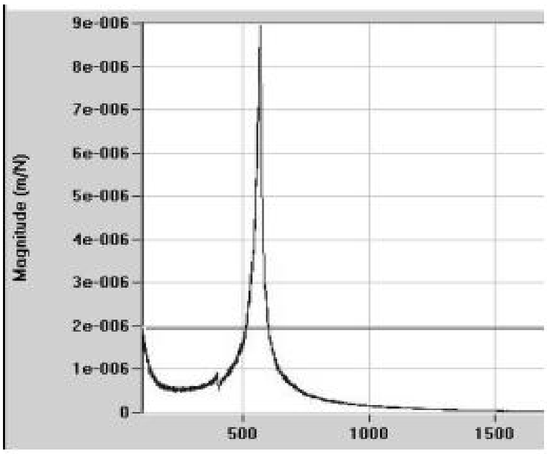
Figure 2.4: Comparison of cutting coefficients

The feed rate for the turning tests are obtained as 0.12 mm/rev. That value will be constant and it will be the feed rate for all the turning tests from now on. $Re(G)_{min}$ is the other unknown in Eq. 1.15.

$Re(G)_{min}$ is the completely real response of the equation. The peak to valley value at the real part of the function gives the $Re(G)_{min}$. Modal tests are performed to determine that value. The impact tests are done on the tool holder for every different clamping length and $Re(G)_{min}$ is observed from the transfer function that is the output of the impact test. The natural frequencies of the tool holders with different clamping lengths are also determined by the impact tests. In turning, the important direction for the analysis is the x-direction in the feed direction and chatter in the z-direction is neglected. So, all the analysis are done for the x-direction of the tool holder. The tests are carried out under the conditions of two different tool holder lengths, 110 and 135 mm in order to determine the effect of the dynamic properties of different tool holder lengths on tool wear.



(a)



(b)

Figure 2.5: TF for the tool lengths 110 mm (a) and 135 mm (b)

Tool length (mm)	Frequency (Hz)	Damping ratio (ζ)	Stiffness (N/m)	Mass (kg)
L=110	948.78	3.1574E-02	1.2742E+07	0.359
L=135	563.94	2.0087E-02	3.2906E+06	0.262

Table 2.2: Dynamic properties of tool holder

(mm)	**L=110**	**L=135**
Severe Chatter	1	0.75
Chatter	0.65	0.5
Chatter limit	0.4	0.25
Stable	0.3	0.15

Table 2.3: Chatter limits for two holder lengths

2.1.3 Determining Stability Limit Procedure in Milling

The determination of the stability limit in milling is more complicated. The spindle speeds in turning are generally about 1000 rpm or less so the lobes in the stability diagram are not as clear as the milling stability lobes. Because of that nature of the diagram, generally the chatter limit in turning is accepted as a line at lower spindle speeds. The stability chart for milling has many undulated lobes. That means there are different chatter limits for every cutting speeds. The modal tests to determine the parameters are applied by CutPro® MalTF software. The dynamic parameters which are obtained from the modal test are shown in Tables 2.4 and 2.5. Similar to the turning tests, milling tests are done under the condition of two different tool lengths, 110 and 120 mm, to see the effect of tool stiffness and dynamic characteristic on tool wear.

Tool length (mm)	Frequency (Hz)	Damping ratio (ζ)	Stiffness (N/m)	Mass (kg)
L=110	730.96	1.4490E-02	1.0484E+07	0.497
L=120	714.06	1.4538E-02	8.0268E+06	0.399

Table 2.4: Dynamic properties of the test tools in x-direction

Tool length (mm)	Frequency (Hz)	Damping ratio (ζ)	Stiffness (N/m)	Mass (kg)
L=110	769.20	1.8731E-02	1.6761E+07	0.717
L=120	728.93	1.9439E-02	1.2360E+07	0.589

Table 2.5: Dynamic properties of the test tools in y-direction

The modal analysis is performed by CutPro® Modal after the modal test. In CutPro® Modal software, some system parameters and information have to be specified. These parameters are the cutting tool properties (length, radius, material, geometrical angles), workpiece material, machining conditions, and dynamic properties (frequency, damping ratio, stiffness). The software analyzes the input data and this procedure results with the determination of the stability lobes. The resultant stability diagrams for different tool lengths are shown in Figures 2.6 and 2.7 for steel.

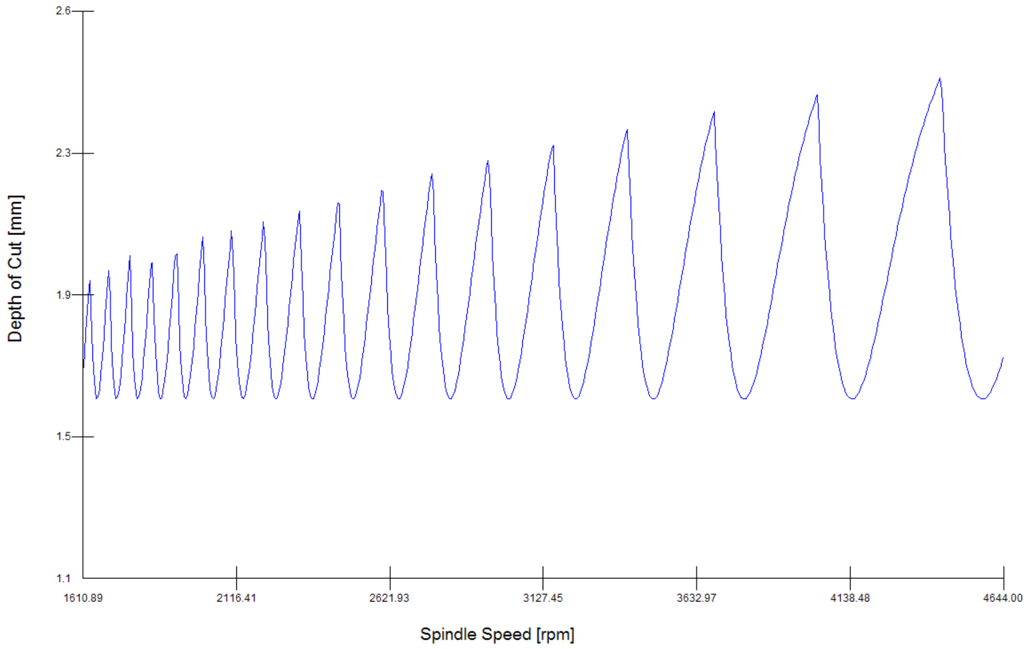


Figure 2.6: Stability diagram for steel at L=110 mm

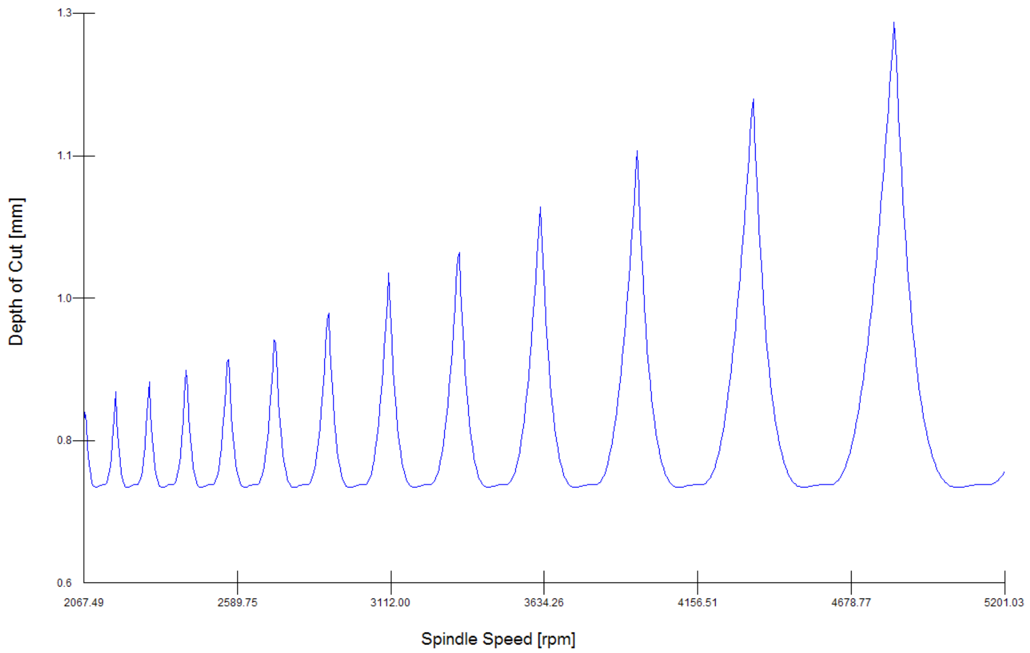
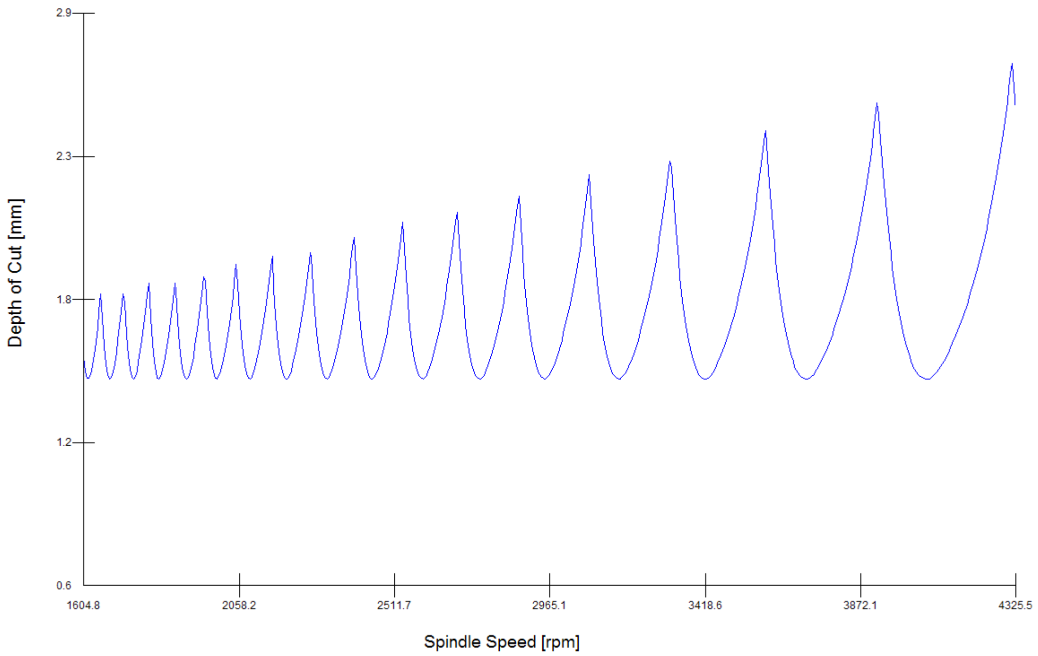
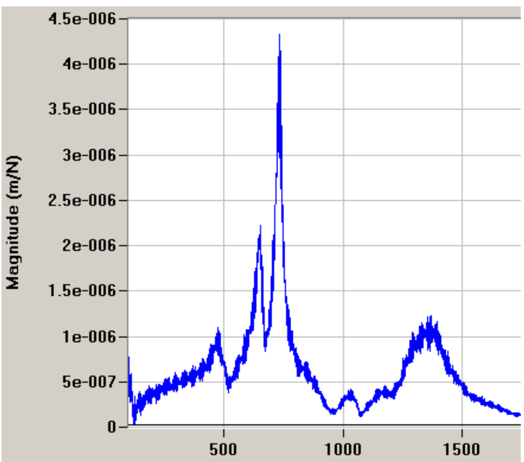


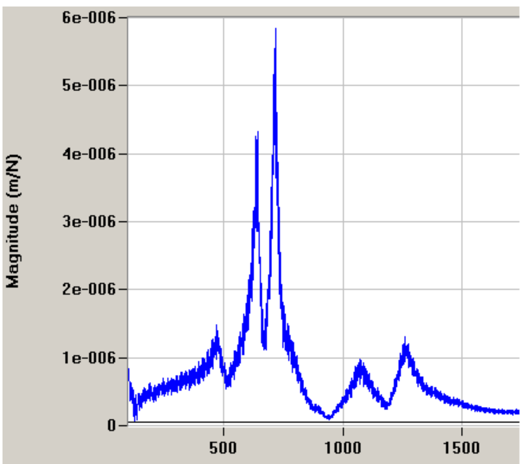
Figure 2.7: Stability diagram for steel at L=120 mm

Another modal analysis is performed for titanium after the modal test. The chatter limit and the stability lobe depend on workpiece material, too. A change in the characteristic of the workpiece material directly affects the stability lobe and other chatter parameters. The same modal parameters in Tables 2.4 and 2.5 are used for the new stability lobe for titanium because all the parameters except workpiece material are the same. The resultant stability diagrams for tool length, 120 mm, for titanium is shown in Figures 2.8 (a). The chatter limit (b_{lim}) for titanium is 1.45 mm.



(a)





(b) (c)

Figure 2.8: Stability diagram for titanium at L=120 mm (a) and TF for the tool lengths 110 mm (b) and 120 mm (c)

2.2 Cutting Conditions

2.2.1 Cutting Conditions in Turning

Different chatter conditions are used in the tests to demonstrate the effects of chatter intensities on tool wear and tool life. Besides dynamic conditions, machining parameters are also important and influential on tool wear and tool life in metal removing processes in order to define the behavior of wear mechanism under chatter conditions at different cutting conditions, different cutting parameters are also applied in the tests. The cutting parameters in a standard turning process are cutting speed (V), feed rate (h) and depth of cut (b). The feed rate is fixed at 0.12 mm/rev as it is explained previously. The depth of cut value varies in every chatter condition and tool holder length. The depth of cut values are obtained as 0.3, 0.65 and 1 mm for tool holder length 110 mm and 0.15, 0.5 and 0.75 mm for tool holder length 135 mm. The depth of cut values are for stable condition (S), chatter condition (C) and severe chatter condition (SC), respectively.

The cutting speed is probably the most important cutting parameter in a machining process. It directly affects the cutting temperature, tool life, surface finish, machining time etc. The effect of the cutting speed on tool life has been known for a long time. In turning tests, three cutting speed levels are used in order to examine the tool life behavior. There are little differences between the test matrix for the three levels of cutting speeds and the experimental cutting speeds. The reason for this difference is the manual machine tool. Lathe on which the cutting tests are performed is a universal lathe. It is not possible to control the spindle speed at the point that desired because it is not a NC machine tool. So the cutting speed cannot be changed while the outer diameter of the workpiece becomes smaller. The cutting speed differences between the test matrix and the experimental values are smaller than 3%, so the speed variation is minimal. The speed matrix for turning tests are shown in Table 2.6. All the tests are applied as dry cutting that means there is no coolant liquid in the cutting process. The inserts are clamped to the tool holder with a torque about 0.8 Nm.

Test no	Holder length (mm)	Cutting speed level (m/min)	Average cutting speed (m/min)	Depth of cut (mm)	Chatter condition
1	110	170	166	0.3	S
2	110	110	110	0.3	S
3	110	50	50	0.3	S
4	110	170	175	0.65	C
5	110	110	114	0.65	C
6	110	50	50	0.65	C
7	110	170	180	1	SC
8	110	110	107	1	SC
9	110	50	52	1	SC
10	135	170	167	0.15	S
11	135	110	126	0.15	S
12	135	50	51	0.15	S
13	135	170	170	0.5	C
14	135	110	116	0.5	C
15	135	50	53	0.5	C
16	135	170	167	0.75	SC
17	135	110	108	0.75	SC
18	135	50	52	0.75	SC

Table 2.6: Test matrix for turning tests

2.2.2 Cutting Conditions in Milling

Different chatter conditions are applied in the milling tests for the examination of the chatter intensities just like in turning. In a milling process, the cutting parameters are the cutting speed, feed rate, axial and radial depth of cut. The cutting speeds are obtained as 170 and 260 m/min. These speed values equal to 2706 and 4138 rpm, respectively. The feed rate is 0.1 mm/tooth and that value is constant for all milling tests. The cutting process is a half-immersion slotting. That means the radial depth of cut is 10 mm, the half of the cutting tool diameter. The axial depth of cut depends on the chatter limit. The radial depth of cuts are obtained for a stable, chatter and severe chatter conditions just like the turning tests. The depth of cut values are 1, 1.8 and 2 mm for tool length 110 mm, and 0.7, 0.85 and 1 mm for tool length 120 mm. The cutting is a dry cutting process with no coolant. That condition decreases tool life and also experimental time.

The metallurgical properties and cutting parameters of titanium are very different from steel. Titanium machining is much harder than the machining of any other materials. So, the cutting conditions have been modified for titanium tests. The cutting speed for titanium tests is decreased to 35 m/min. That speed equals to 557 rpm. The feed rate was kept constant for titanium tests at 0.1 mm/rev. Depth of cut values are 1, 2 and 2.5 mm for stable, chatter and severe chatter conditions, respectively. The cutting type is half-immersion slotting again. It is very dangerous to machine titanium under dry conditions and because of that reason, the cutting of titanium is performed under wet cutting condition. The coolant is a water based coolant. It must be considered that existence of coolant in the process decreases cutting temperature and increases tool life.

The cutting tool has two teeth but only one insert is used in order to prevent the wear difference between two different teeth. The cutting tool is clamped to the holder with a torque about 35 Nm for both tool lengths. The cutting matrix for milling tests is shown in Table 2.7.

Test no	Tool length (mm)	Cutting speed (m/min)	Depth of cut (mm)	Chatter condition
1	110	170	1	S
2	110	260	1	S
3	110	170	2	C
4	110	260	1.8	C
5	120	170	0.7	S
6	120	260	0.7	S
7	120	170	1	C
8	120	260	0.85	C
9*	120	35	1	S
10*	120	35	2	C
11*	120	35	2.5	SC

Table 2.7: Test matrix for milling tests (*Titanium)

2.3 Test Materials and Equipments

2.3.1 Workpiece

2.3.1.1 Steel

In both tests, turning and milling, the same material, AISI 1040 steel is used. That material is a medium carbon steel as cold drawn and it is very commonly used in manufacturing. Typical uses of AISI 1040 steel include machine, plow, and carriage bolts, tie wire, cylinder head studs, and machined parts, U-bolts, concrete reinforcing rods, forgings, and non-critical springs. The metallurgical properties of the material is shown in Table 2.8 and the mechanical properties of the material is shown in Table 2.9. The workpiece for the turning tests is a round bar which has 100 mm of diameter and 500 mm of length. The workpiece for the milling tests is a rectangular block about the dimensions 80, 80 and 400 mm.

Component	Wt. %
C	0.37-0.44
Fe	98.6-99
Mn	0.6-0.9
P	max 0.04
S	max 0.05

Table 2.8: Metallurgical properties of AISI 1040 steel

Hardness, Brinell	149
Hardness, Rockwell	80
Tensile Strength, Ultimate	515 MPa
Tensile Strength, Yield	450 MPa
Modulus of Elasticity	200 Gpa
Bulk Modulus	140 MPa
Shear Modulus	80 GPa
Poisson's Ratio	0.29

Table 2.9: Mechanical properties of AISI 1040 steel

2.3.1.2 Titanium

Titanium and its alloys exhibit a unique combination of mechanical and physical properties and corrosion resistance which have made them desirable for critical, demanding aerospace, industrial, chemical and energy industry service. Titanium alloys offer a wide spectrum of strength and combination of strength and fracture toughness. The milling of titanium is a more difficult operation than that of turning. The cutter mills only part of each revolution, and chips tend to adhere to the teeth during that portion of the revolution that each tooth does not cut. On the next contact, when the chip is knocked off, the tooth may be damaged. [40].

In milling tests (T9, T10 and T11), most commonly preferred Ti alloy, $TiAl_6V_4$, is used. $TiAl_6V_4$ is an alpha-beta alloy and it is very popular in aero-engines. The metallurgical properties of the material is shown in Table 2.10 and the mechanical properties of the material is shown in Table 2.11. The workpiece for the milling tests is a rectangular block about the dimensions 35, 104 and 305 mm.

Component	Wt. %
Al	6
Fe	max 0.25
O	max 0.2
Ti	90
V	4

Table 2.10: Metallurgical properties of titanium alloy

Hardness, Brinell	334
Hardness, Rockwell	36
Tensile Strength, Ultimate	900 MPa
Tensile Strength, Yield	830 MPa
Modulus of Elasticity	114 Gpa
Shear Modulus	44 GPa
Poisson's Ratio	0.33

Table 2.11: Mechanical properties of titanium alloy

2.3.2 Cutting Tools and Holders

2.3.2.1 Cutting Tools and Holders in Turning

The insert for the turning tests is a ISCAR DCMT 11T304-14 IC20 as shown in Figure 2.8. It is a carbide insert with no rake and oblique angles. Normally, that cutting tool is not the best fit for that material but it is very critical to have tool wear as soon as possible in the test period so that insert is used in the tests.

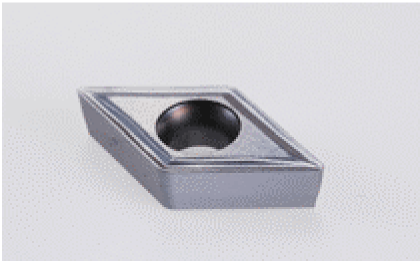
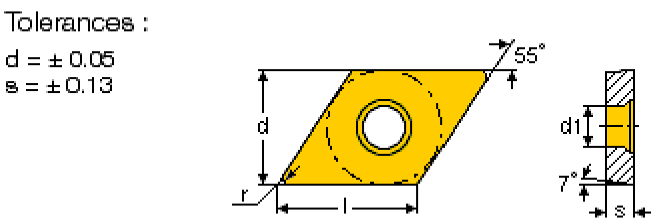


Figure 2.9: The insert for the turning tests

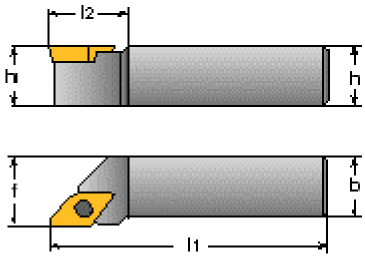


l	11.6
d	9.52
s	3.97
r	0.8
$\varnothing d_1$	4.4

Figure 2.10: Geometrical properties of the turning inserts (in mm)

The tool holder for that insert is a ISCAR SDJCR/L 2525M-11 as shown in Figure 2.11. It is a screw clamp for that kind of inserts.

Figure 2.11: The tool holder for the turning tests

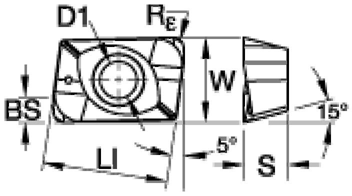


h	25
h_1	25
l_1	150
l_2	28
f	32
f_1	0

Figure 2.12: Geometrical properties of the tool holder (in mm)

2.3.2.2 Cutting Tools and Holders in Milling

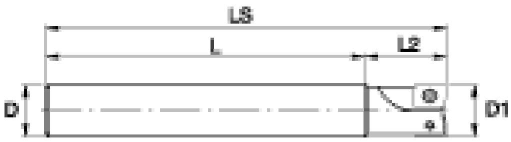
The insert for the milling tests is a ADKT1622PDSR5LC KC725M as shown in Figure 2.13. It is a carbide insert with a relief angle about 15^0. The insert is PVD coated and the coating material contains three coating layers TiN, TiCN and again TiN, respectively. An uncoated tool would be better for the milling tests but for this tool holder and geometry, uncoated inserts are not available in the market. That insert is generally used for end milling operations and it has a T-land for edge strength.



BS	2.16
D1	2.90
Rε	0.79
LI	10
W	6.70
S	3.50

Figure 2.13: Geometrical properties of the milling inserts (in mm)

Figure 2.14 shows the tool holder for milling inserts, Kennametal 20A02R050A20SAD10. It is a two flute milling tool holder for die and mold operations.



D	20
D1	20
L	150.000
L2	50.170
LS	200.170

Figure 2.14: Geometrical properties of the tool holder (in mm)

2.3.3 Machine Tools

In turning tests, a TOS SN50C universal lathe is used. It is powered by a 6.6 kV electric motor. The machine tool has a maximum capacity of 250 mm diameter and 1000 mm workpiece length.

Figure 2.15: TOS SN50C universal lathe

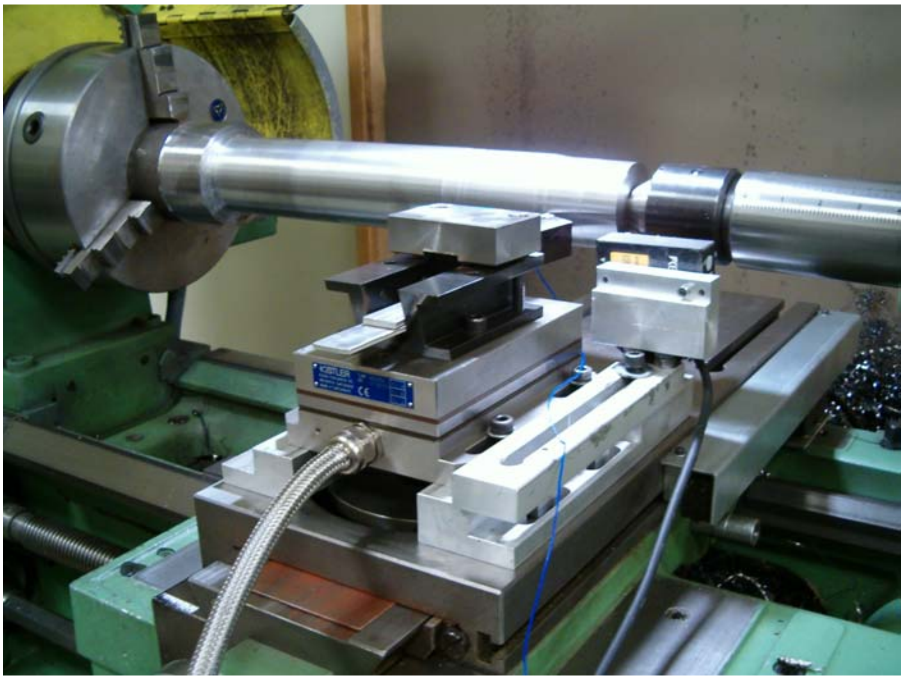
All the milling tests are carried out on a Deckel Maho DMU 50 5-axis machining center. The machine has 18 000 rpm maximum spindle speed and relatively high torque output for a high speed machine.

Figure 2.16: DMU 50 machining center

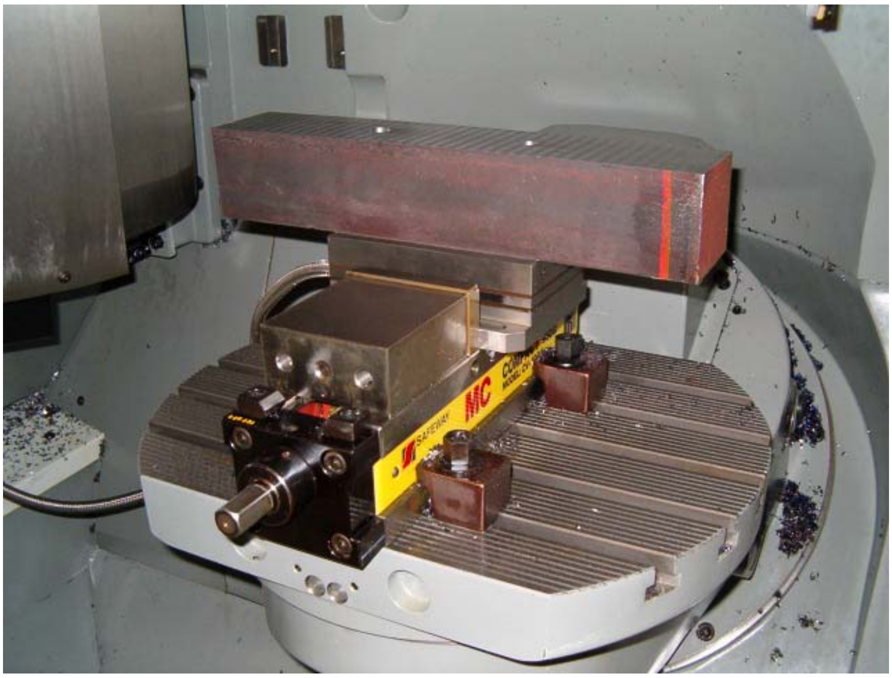
2.3.4 Measurement and DAQ Equipments

Vibration and force data are collected by different sensors and transferred to a portable computer by a data acquisition (DAQ) system. The DAQ system components for taking measurements are shielded cables which carry over signals by preventing against electrical noise, a BNC board which collects all signals from different sources or cables, and a DAQ card which transfers the signals from the BNC board to the computer. The data, which are transferred to the computer, are displayed by a software called Labview.

The cutting forces are recorded during all machining tests by a Kistler 9257BA force dynamometer. In turning tests, the tool holder is settled on a fixture and that fixture is bolted on the force dynamometer as shown in Figure 2.17 (a). In milling tests, the workpiece block is bolted on the force dynamometer which is clamped by a vice as shown in Figures 2.17 (b). The cutting forces are measured continuously in all tests in order to determine the effects of tool wear and chatter on cutting forces. The dynamometer is used to gather the force signals which are amplified and recorded using a custom written LabView program on a laptop computer as shown in Figure 2.17 (c).



(a)



(b)

(c)

Figure 2.17: Cutting force measurement

The vibration data are collected by a Keyence LK 031 laser displacement sensor during the turning tests. The laser sensor is placed on a sliding fixture as shown on the right hand side of Figure 2.17 (a). The sensor has a resolution about 1μm.

Tool wear is measured by using a Nikon MM 40 video microscope shown in Figure 2.18. The rake and flank faces of the inserts are inspected during the cutting tests ever so often. The photos of worn tools are also taken during the wear measurements.

The worn tools are inspected in detail by a LEO Supra 35VP scanning electron microscope (SEM) as shown in Figure 2.19. It is able to see the metallurgical details of the wear zone by SEM inspections. The magnifying rate for SEM inspections varies between 50 and 10500 times greater than the original size.

Figure 2.18: Microscope for tool wear measurements

Figure 2.19: SEM for detailed inspections

2.4 Summary

The test methodology is told in chapter 2. Different cutting parameters and chatter conditions are applied during the machining tests in order to examine effects of various chatter intensities and parameters on tool wear. Two different workpiece materials are used in milling tests in order to see the behavior of chatter conditions for different materials. The analysis and measurements before the cutting tests, test matrixes, data collection and measurements during the tests, the materials and equipments used during all the thesis procedure are also explained.

CHAPTER 3

EXPERIMENTAL RESULTS

Different data have been collected through measurements done before, during and after the cutting tests. Cutting forces, vibration amplitudes, tool wear and surface roughness were measured and analyzed. Turning and milling test methodologies were explained in the previous chapter. In this chapter, the results of these measurements are analyzed and discussed.

3.1 Turning Tests

The total machining time in turning tests is more than 700 minutes and total cutting distance is 60.2 km. Cutting forces, vibration amplitudes, tool wear and surface finish are measured.

3.1.1 Tool Wear

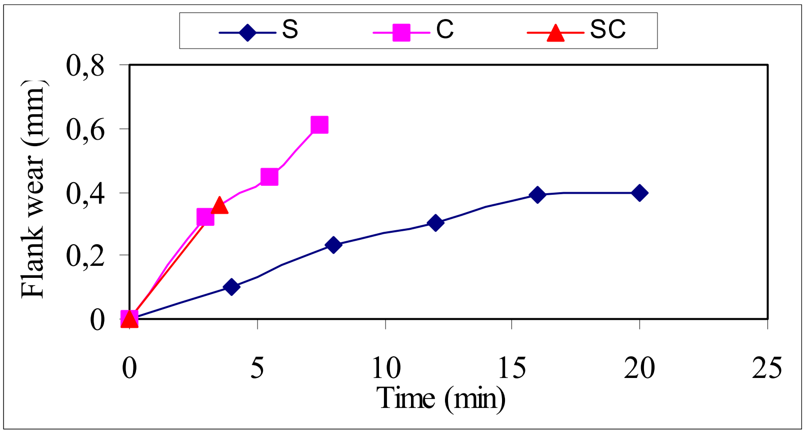
The tool wear is measured several times throughout the total life of the tool. The time interval between two tool wear measurements varies between 2 and 11 minutes depending on the wear rate. The notch wear was considered in the measurements in order to reduce test time since it progresses much faster than the flank wear. Maximum wear land of 0.2 mm is used as the tool life criteria. Note that maximum allowable wear depends on the application, i.e. higher wear can be tolerated in roughing operations whereas much less wear is allowed in finishing due to surface quality issues.

In the tests, the chatter condition is obtained using a depth of cut which is very close to the chatter limit for that case. The severe chatter condition is obtained by further increasing the depth of cut more than 50% of the chatter limit as shown in Table 2.6.

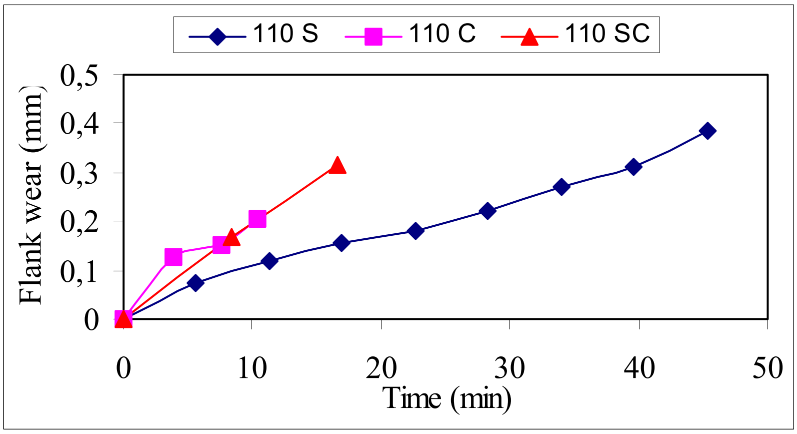
Test no	Chatter condition	Wear time (min)	Cutting distance (m)	Vibration amplitude (mm)
1	S	7	1164	0
2	S	25.5	2815	0
3	S	73.3	3677	0
4	C	1.6	280	0.007
5	C	10.4	1187	0.022
6	C	63	1750	0.012
7	SC	2.8	1800	0.011
8	SC	10	3531	0.027
9	SC	23	146	0.015
10	S	19	3171	0
11	S	44	5542	0
12	S	73	2693	0
13	C	2.2	373	0.007
14	C	7.2	835	0.009
15	C	55	2915	0.009
16	SC	2	334	0.016
17	SC	4	434	0.023
18	SC	29.5	1527	0.020

Table 3.1: Result of turning tests

The wear data collected in the tests are given in Table 3.1. The data are drawn in different forms to demonstrate the dynamic effects on tool wear better. Figure 3.1 shows the progress of the tool wear with cutting time for shorter holder length of 110 mm and for cutting speeds of 170, 110 and 50 m/min. In each of the graphs, 3 curves are shown corresponding to stable, chatter and severe chatter conditions. The same data are presented for 135 mm holder length in Figure 3.2.



(a)



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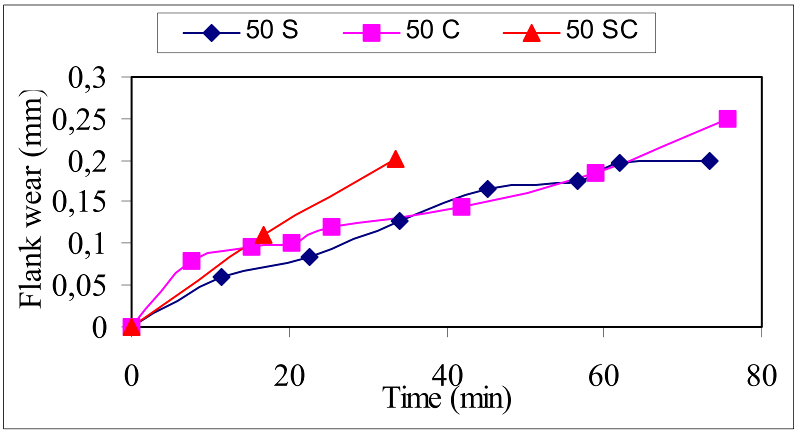
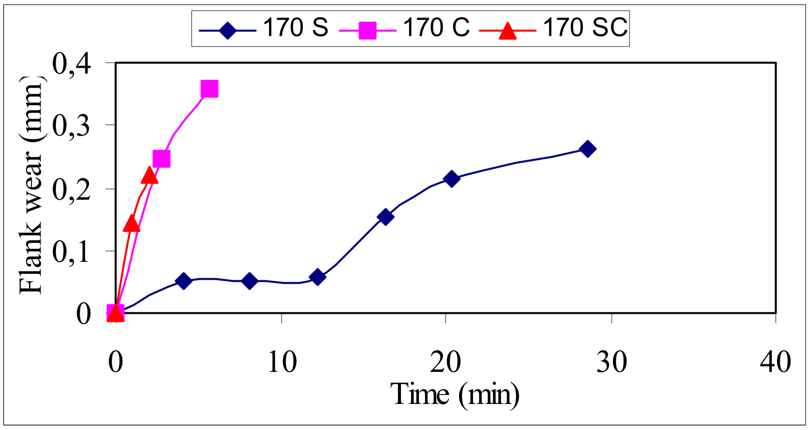
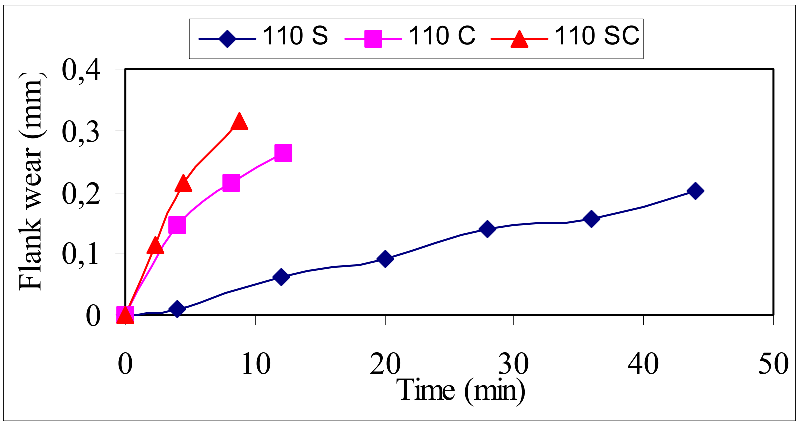


(c)

Figure 3.1: Tool wear vs. cutting time for different chatter conditions and cutting speeds (L=110 mm)



(a)



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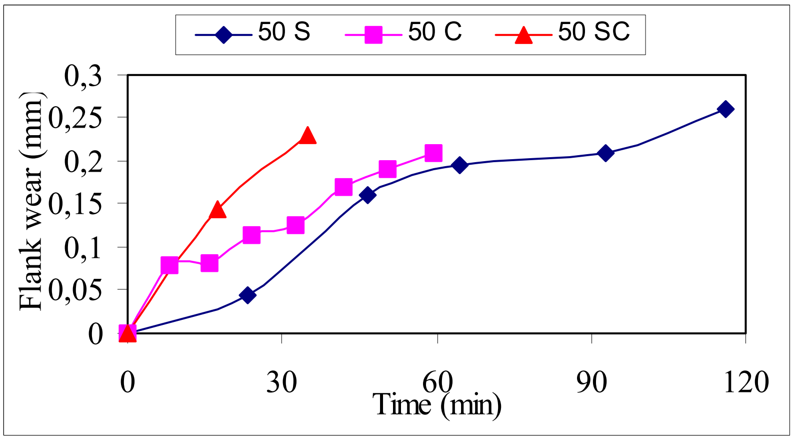


(c)

Figure 3.2: Tool wear vs. cutting time for different chatter conditions and cutting speeds (L=135 mm)

The tool wear development graphs for two tool holder lengths in different cutting speeds, 50, 110 and 170 m/min, and different vibration conditions, stable, chatter and severe chatter, are shown in Figures 3.1 and 3.2. These figures show that the effect of chatter on tool wear becomes more predominant for higher speeds. At higher speeds, the tool life is reduced by several times. Also, for lower stiffness case (L=135 mm), the reduction in the tool life due to chatter is much higher. Shorter tool length increases the tool life even at stable conditions. The results are compiled in the following figures to demonstrate these effects better.

Figure 3.3 shows the tool life chart for shorter tool length for chatter and severe chatter conditions. Tool life criteria of 0.2 mm flank wear has been used to develop these charts. It can be seen that the tool life decreases as the chatter severity increases. The same chart is given for L=135 mm in Figure 3.4 where similar effects are seen.

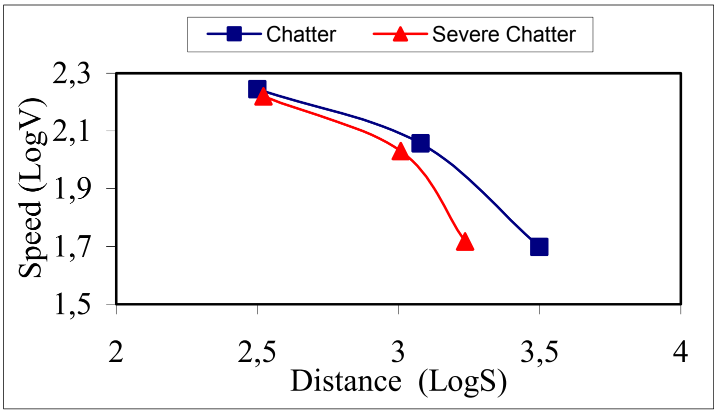


Figure 3.3: Cutting distance vs. speed for L=110 mm

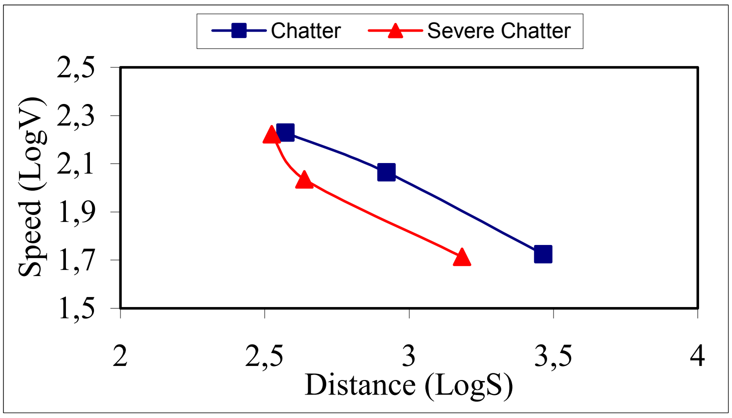


Figure 3.4: Cutting distance vs. speed for L=135 mm

Figure 3.5 shows the effect of holder length on tool life for severe chatter conditions. It can be concluded from these results that the tool life is strongly affected by the holder length, i.e. stiffness and chatter frequency.

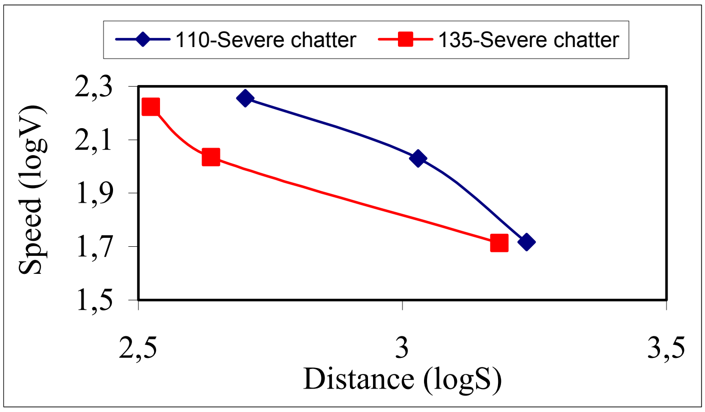


Figure 3.5: Cutting distance vs. speed for different holder length for severe chatter conditions

The Taylor tool life parameters in Eq. 1.1 can be determined for stable and chatter conditions from the cutting time vs. speed charts. These are given in Figures 3.6 and 3.7 for short and long holder lengths, respectively. These charts demonstrate the effect of the chatter on tool life clearly. The identified tool wear parameters are given in Table 3.2.

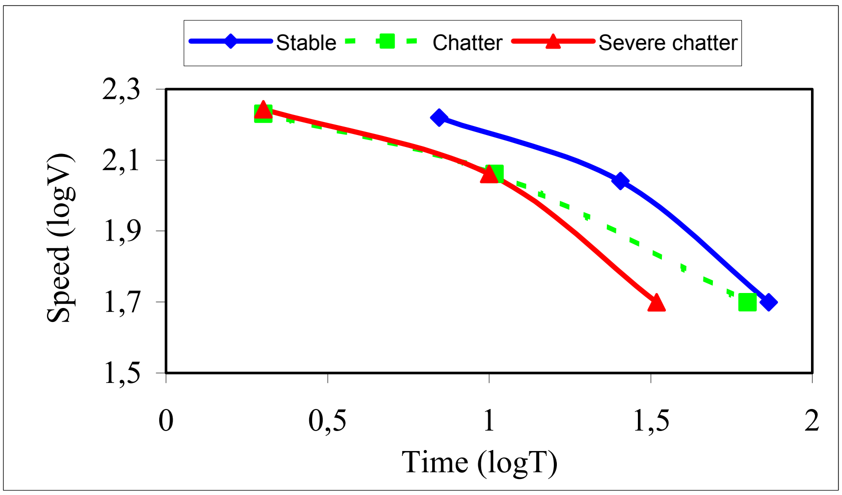


Figure 3.6: Cutting time vs. speed for L=110 mm

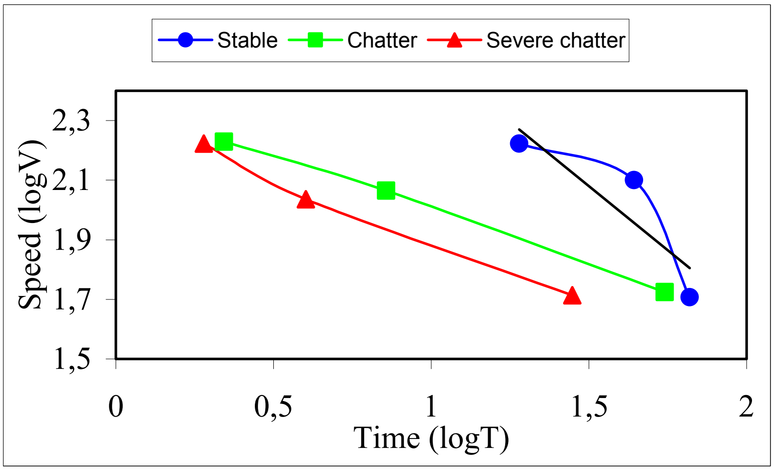


Figure 3.7: Cutting time vs. speed for L=135 mm

	L=110 mm			L=135 mm		
	S	C	SC	S	C	SC
C	2,678	2,344	2,499	3	2,363	2,323
n	0,533	0,354	0,5257	0,6	0,365	0,427

Table 3.2: C and n values identified from wear data in turning tests

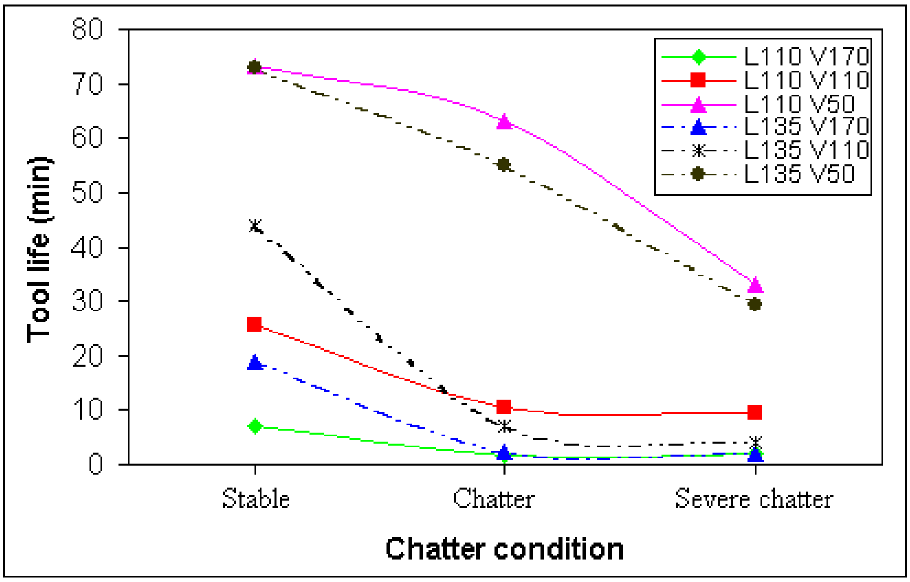
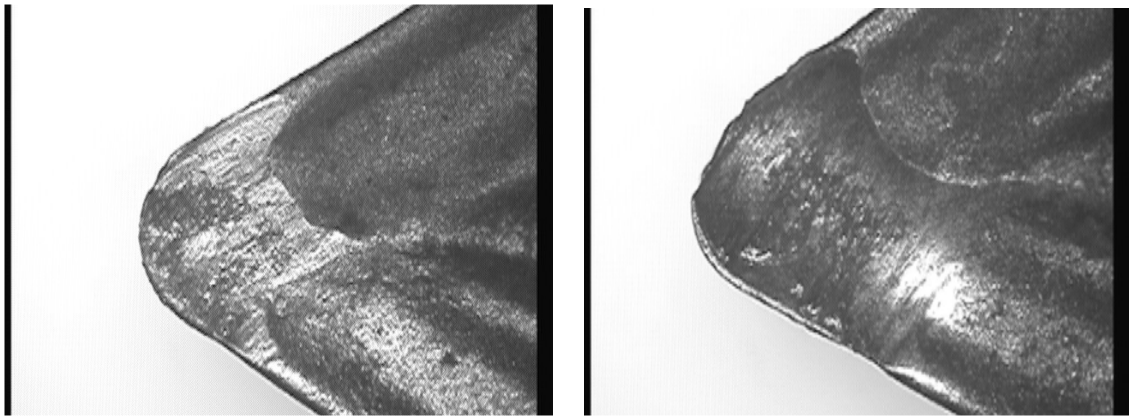


Figure 3.8: Tool life in different dynamic conditions and cutting speeds

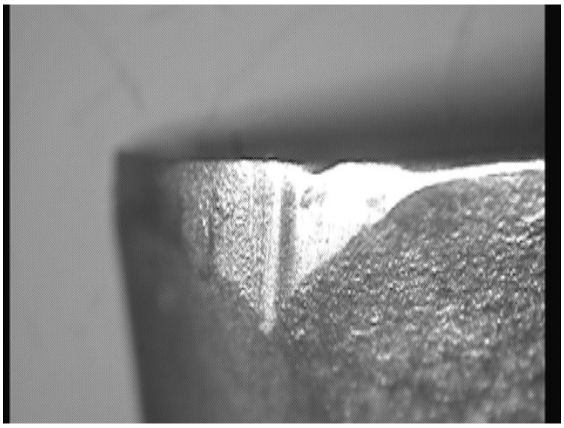
The test results are summarized in Figure 3.8. This figure shows that the tool life is reduced up to and more than 50% due to chatter. This represents a significant increase in tool cost due to vibrations in cutting. The behaviors of the same cutting speeds at different tool lengths are similar. The tool life becomes similar at high vibration amplitudes with the increase of severity of chatter.



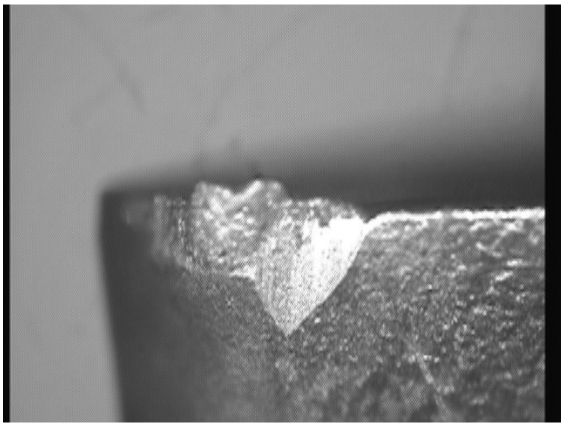
(a) (b)

Figure 3.9: Worn tools after T5 (a) and T7 (b)

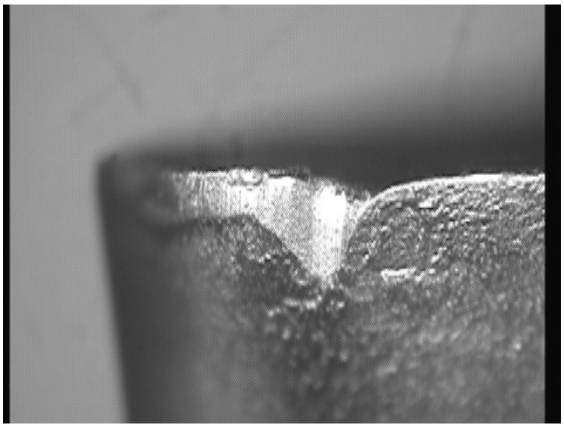
Figure 3.9 (a) and 3.9 (b) show the effect of chatter severity on tool wear. These are the inserts of T5 under chatter and T7 under severe chatter at the same cutting speed (V=110 m/min) and tool holder length (L=110 mm) in turning. The length of crater wear in the horizontal direction is 1,12 mm for T5 insert and 1,65 mm for the T7 insert. The severe chatter damages the rake face of the tool 50% more than chatter condition. The depth of crater wear is very much at severe chatter condition. Chippings are observed under severe chatter. The cutting tool material is broken by micro pieces and that damages the cutting edge of the tool. Chipping of the edge leads to shorter tool life and poor surface finish.



(a)



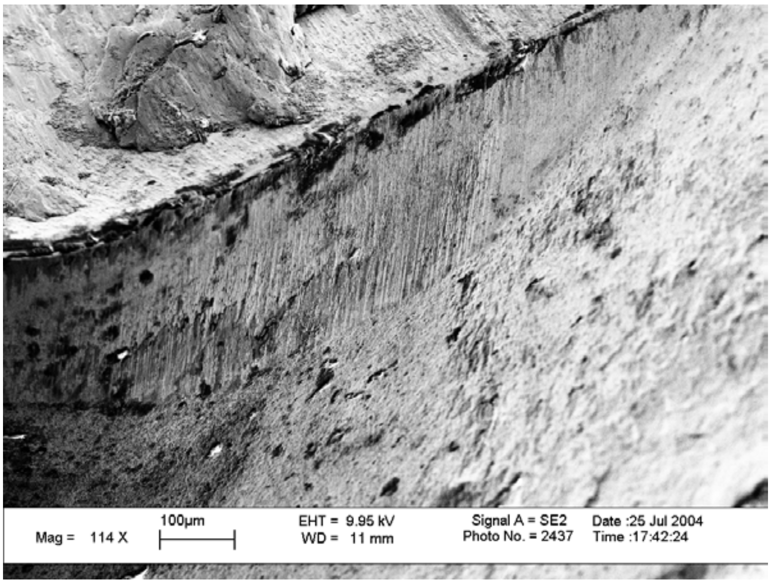
(b)



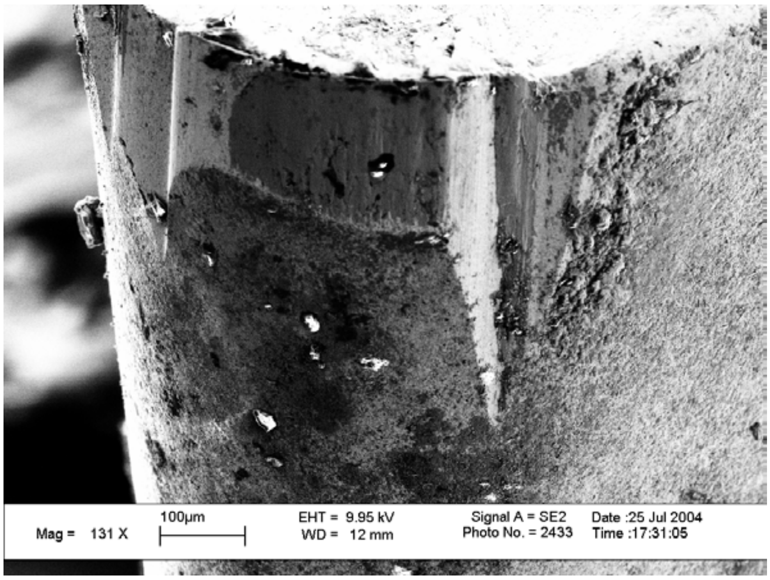
(c)

Figure 3.10: Worn tools after T13 (a), T14 (b) and T15 (c)

Figure 3.10 shows the effect of cutting speed on tool wear under chatter condition in turning. The cutting speed is V=170 m/min and total machining time is 5 minutes for T13. The cutting speed is V=110 m/min and total machining time is 12 minutes for T14. The cutting speed is V=50 m/min and total machining time is 60 minutes for T15. The flank wear of T13 after 5 minutes is 360 μm. That is 35% more than the flank wear of T14 (265 μm) and 70% more than the flank wear of T15 (210 μm). The effect of cutting speed on the total wear of the tool is significant.



(a)



(b)

Figure 3.11: SEM view of T9 (a) and T1 (b)

The SEM views of T9 under severe chatter condition and T1 under stable are shown in Figure 3.11. The cutting speeds and the tool lengths are the same for both inserts. The wear on the nose radius and the notch is clearly shown in Figure 3.11 (b). The wear characteristic is regular for stable cutting and there is no extra deformation on the nose radius after 24 minutes. Figure 3.11 (a) shows the wear characteristic under severe chatter condition. The chipping on the cutting edge is obvious and local exfoliations of the cutting tool material exist on the flank face of the tool. The reason for these local extreme deformations can be the impacts of the tool under chatter vibration. The intensity of vibration amplitude is also distinctive on that kind of wear.

3.1.2 Vibration Amplitude

The vibration amplitudes are measured during the cutting tests using a laser displacement sensor. The peak amplitude varies from 5 μm to 25 μm depending on the severity of the chatter and cutting speed as shown in Figures 3.1 and 3.12. The figure also shows that the chatter amplitudes are higher for longer and less stiff holder.

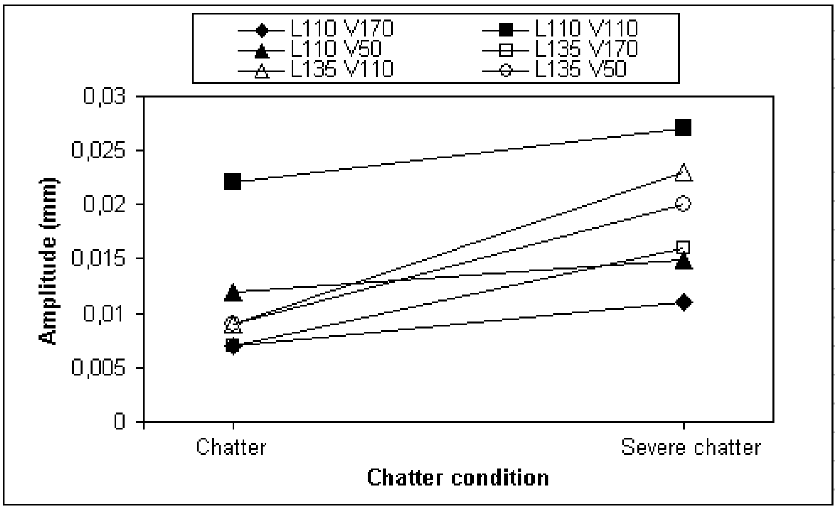


Figure 3.12: Amplitude variation by chatter condition and cutting speed

The effect of the chatter amplitude on tool life is shown in Figure 3.12. As it can be seen from this figure, too, the tool life is reduced significantly with the increasing vibration amplitude at all cutting speeds. However, as mentioned before the reduction at higher speeds are more which cannot be seen in Figure 3.13 clearly due to scaling.

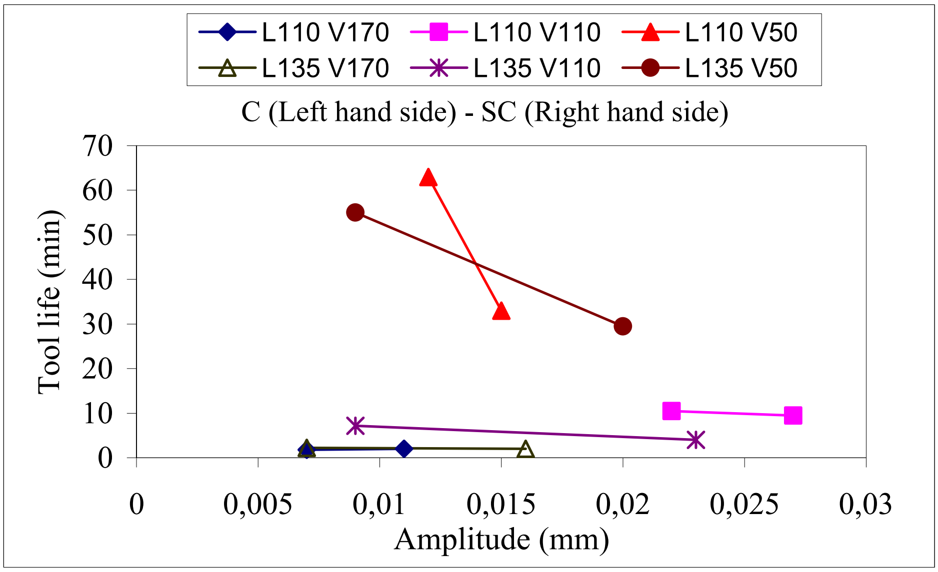


Figure 3.13: Effect of chatter amplitude on tool life

3.1.3 Cutting Forces

The cutting forces are increased due to vibrations as expected. The increase of cutting forces in chatter condition reaches up to 2 times more than the cutting forces in stable condition and the increase of cutting forces in severe chatter condition reaches up to 9 times more than the cutting forces in stable condition. The cutting forces are increased as cutting proceeds. That increase in cutting force is related to the increase of the friction coefficient and enlargement of the wear zone during the process. The cutting forces can increase up to 50% of the starting cutting force in some cases. That increase in cutting forces is pronounced in chatter conditions.

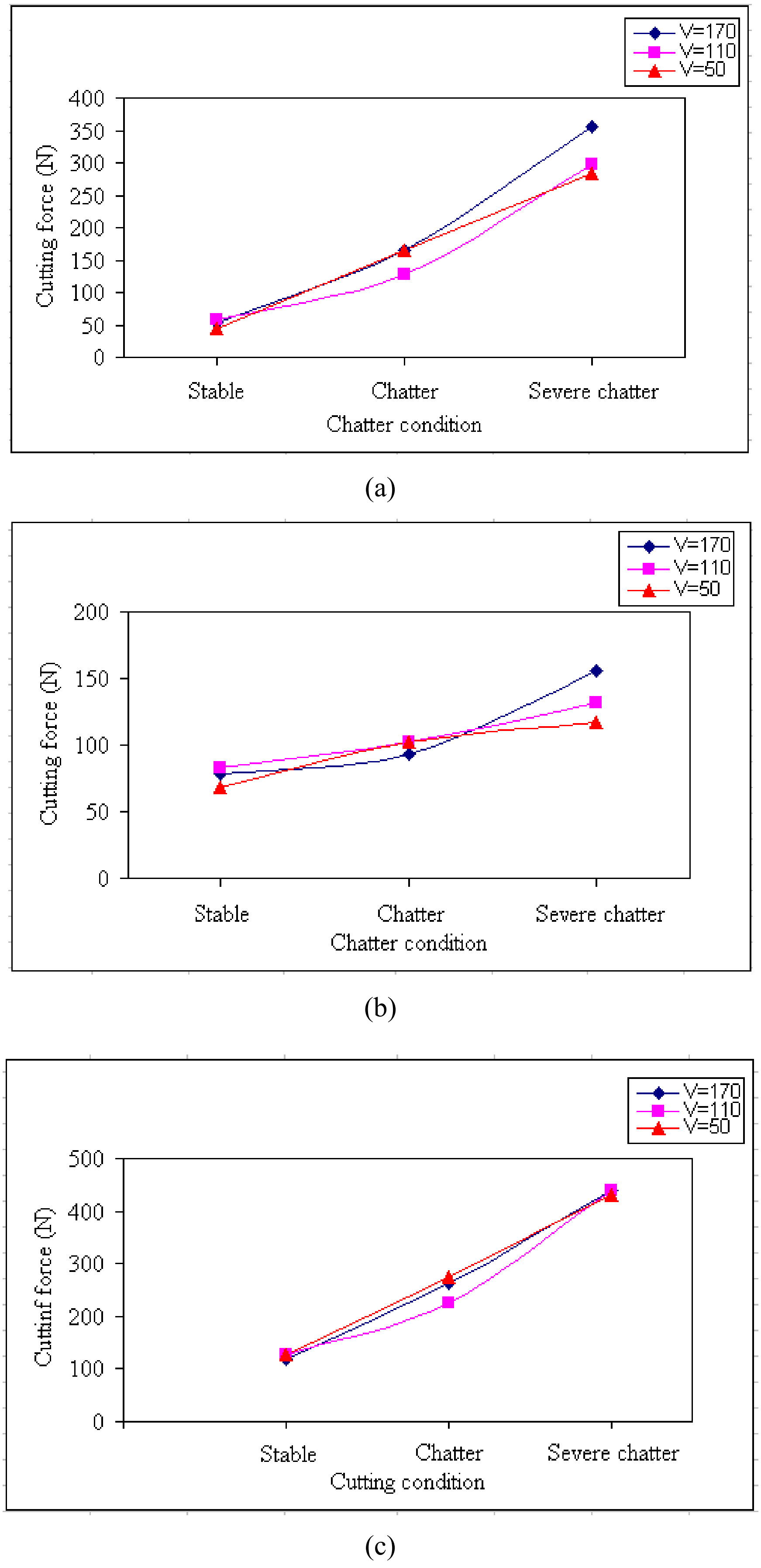
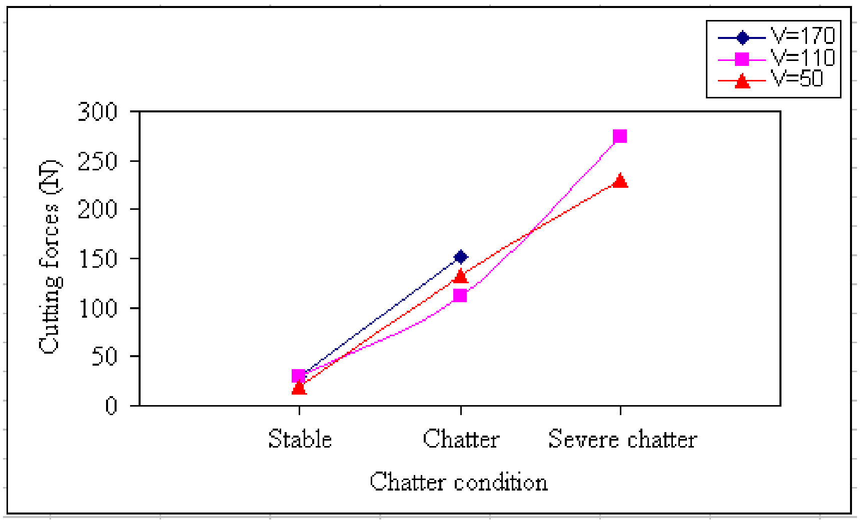
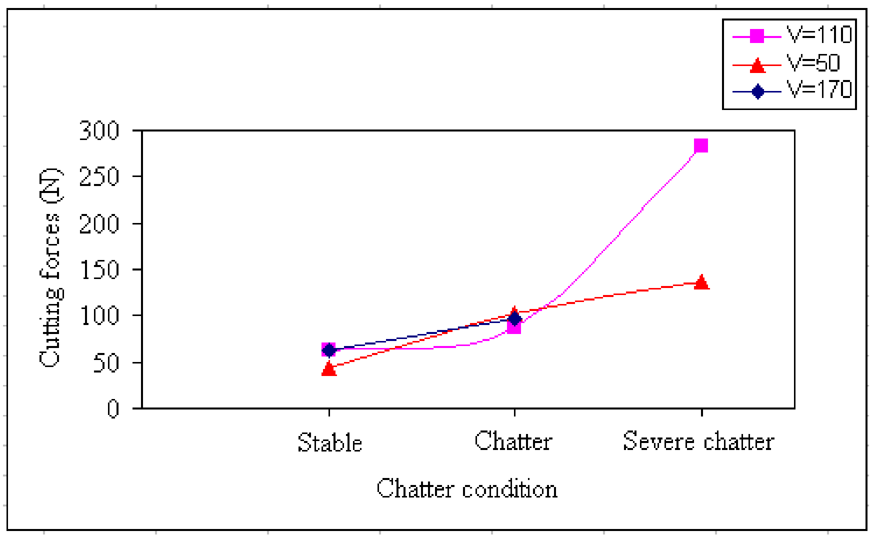


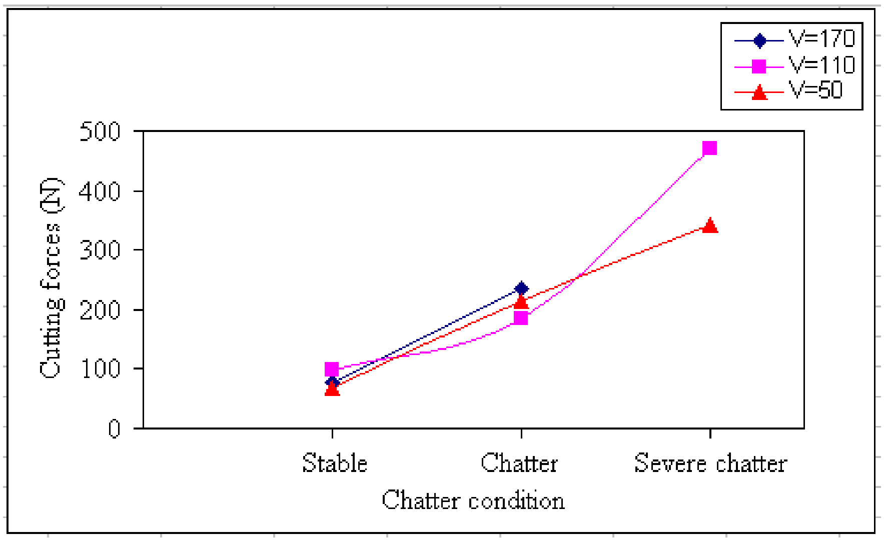
Figure 3.14: F_x (a), F_y (b) and F_z (c) values at different chatter conditions for L=110 mm



(a)



(b)



(c)

Figure 3.15: F_x (a), F_y (b) and F_z (c) values at different chatter conditions for L=120 mm

The cutting forces for different chatter conditions are shown in Figures 3.14 and 3.15. The increase of all cutting force components with the severity of chatter is obvious. The view of the software which collects the cutting force data is shown in Figure 3.16.

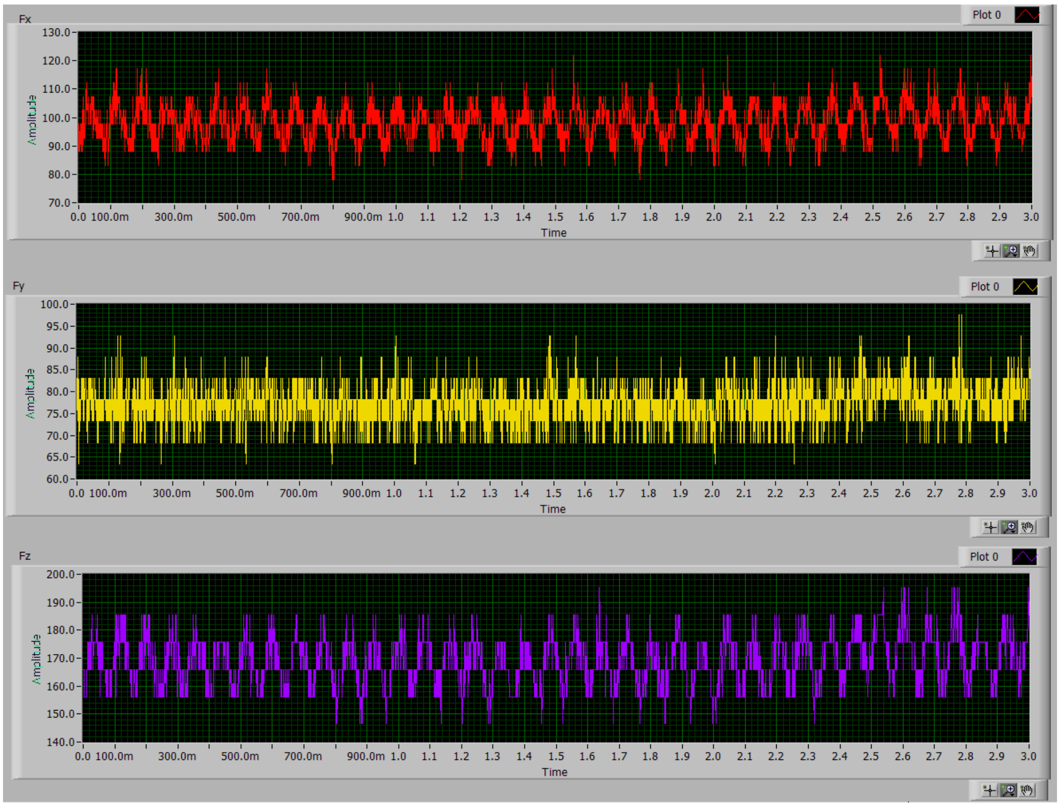
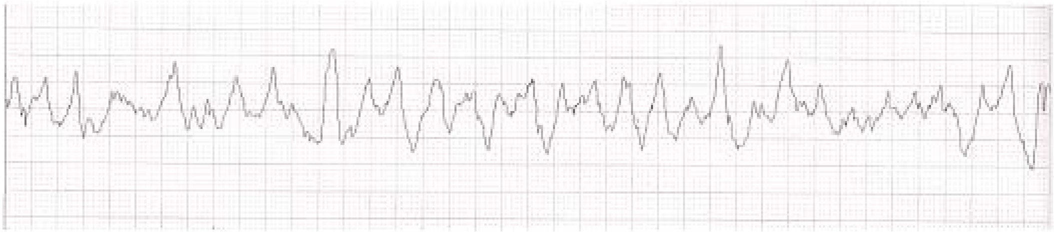


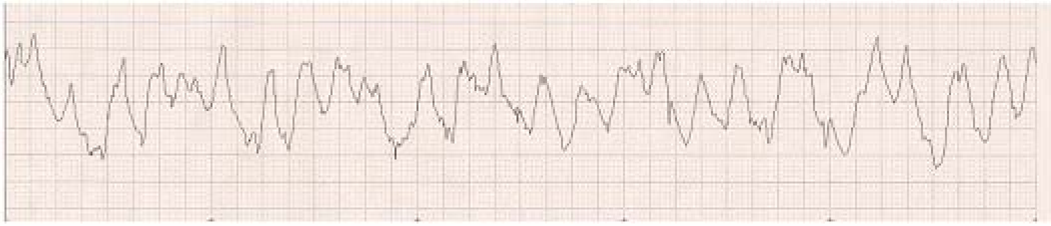
Figure 3.16: Turning forces for T14

3.1.4 Surface Roughness

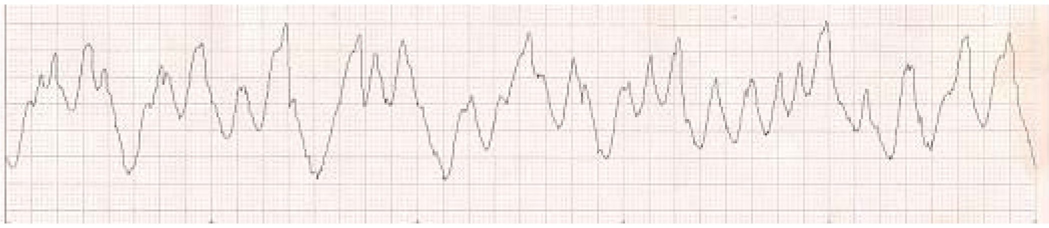
One of the ways to recognize chatter is the chatter marks on the cut surface. Chatter vibrations leave a wavy surface behind. The main reason for this poor surface finish is the vibration of the tool while cutting. These vibrations lead undulations on the tool path. The surface finish is measured for tests in experiments. The surface finish qualities (R_a) after T2, T5 and T8 are 2.85, 4.6 and 5.1 μm, respectively. It is clear that the severe chatter results in surface quality nearly two times worse than the stable cutting. The surface finish reports of the tests are shown in Figure 3.17. The scales for Figure 3.14 are 5 μm per box in vertical and 100 μm per box in horizontal directions.



(a)



(b)



(c)

Figure 3.17: Surface roughness reports for T2, T5 and T8

3.1.5 Summary of Turning Tests

The observations of turning tests bring some conclusions. Chatter results in significant reduction on tool life about 50% for most of the cases and more than 80 % in some high speed cases as shown in Figures 3.1 and 3.2. And also the effects of chatter on tool life are more significant at higher cutting speeds. Figures 3.1 (a) and 3.2 (b) are examples for this situation. Vibration amplitude has direct influence on tool life. Higher vibration amplitude means lower the tool life. The benchmark of Table 3.1 and Figure 3.8 shows the effect of vibration amplitude. That effect is more significant for longer tools. The rigidity of the cutting system has strong influence on tool life. Less rigid tool holder results in higher tool life at stable conditions in turning tests. When depth of cut is increased beyond the chatter limit, the increase of the vibration amplitude is much higher for less rigid tool holding system resulting in higher reduction in tool life as shown in Figure 3.8 and Table 3.1.

3.2 Milling Tests

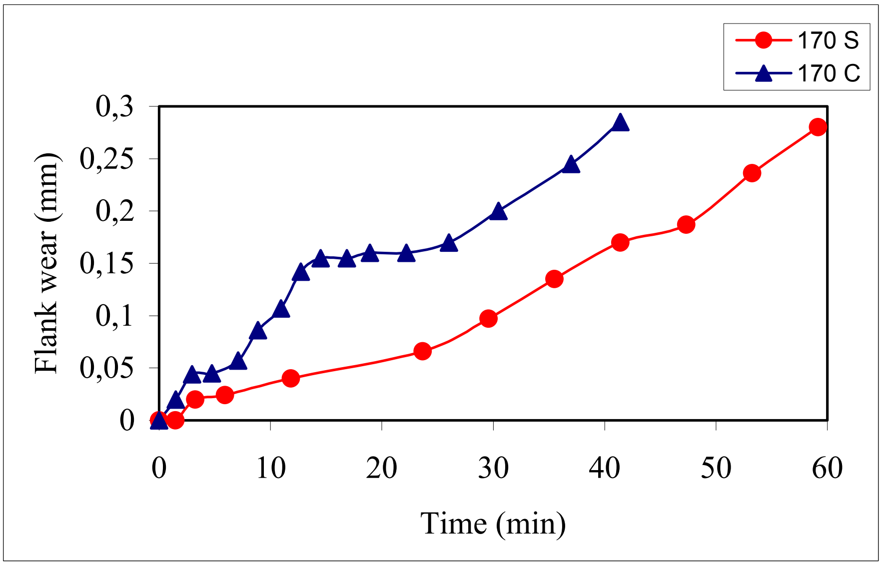
The milling tests are done in order to see the results of the turning tests are the same or not in different machining applications. Two different cutting speeds (170 and 260 m/min) are used to see the effect of speed in the process and two different tool lengths are used to clarify the effect of tool rigidity on tool life. Contrary to turning tests, two different workpiece materials are used in milling tests in order to see the behavior of different metals and whether material type affects the results of chatter vibration on tool life. So, steel (AISI 1040) and titanium ($TiAl_6V_4$) are used as workpiece materials in milling tests. The cutting direction is down-milling and the cutting type is half-immersion. The axial depth of cut in every test varies according to the results of the modal analysis. These results depend on the tool length, workpiece material and cutting speed.

The total machining time in milling tests is more than 500 minutes and total machined material is near to 20 kg. Cutting forces and tool wear are measured and the worn tools are examined in detail.

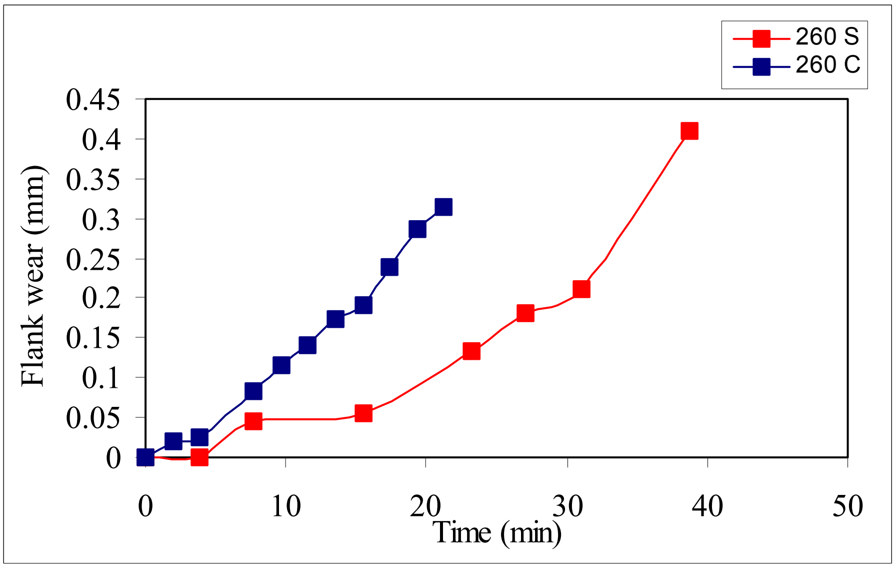
3.2.1 Tool Wear

The tool wear is measured for many times throughout the total cutting time of the tool. The time interval between two tool wear measurements varies between 1,5 and 12 minutes. The flank wear is examined during the measurements and maximum wear land of 0.2 mm is used as the tool life criteria.

The graphs of development of the tool wear while machining of steel for different cutting speeds, 170 and 260 m/min, and two tool holder lengths, 110 and 120 mm, are shown in Figure 3.18 and 3.19. All of these tests are done for two different cutting conditions, stable and chatter.

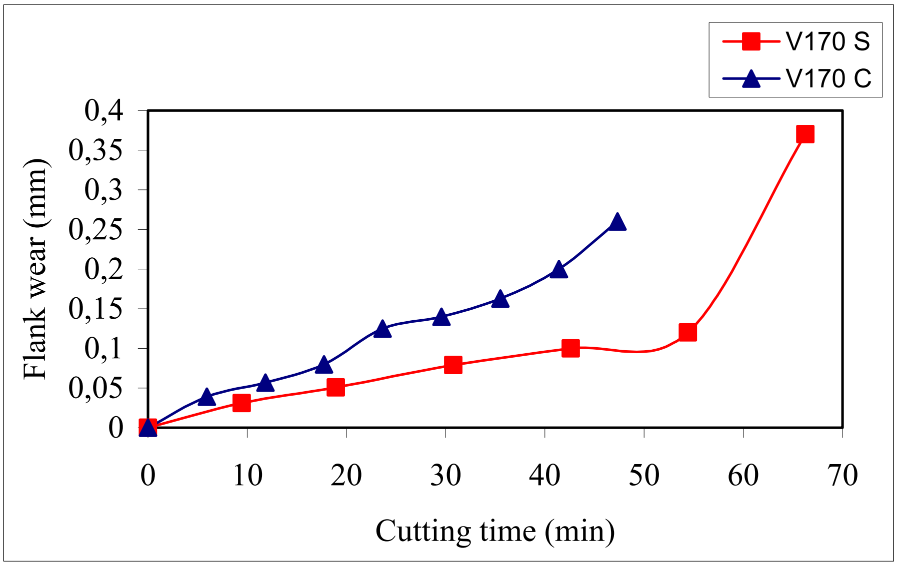


(a)

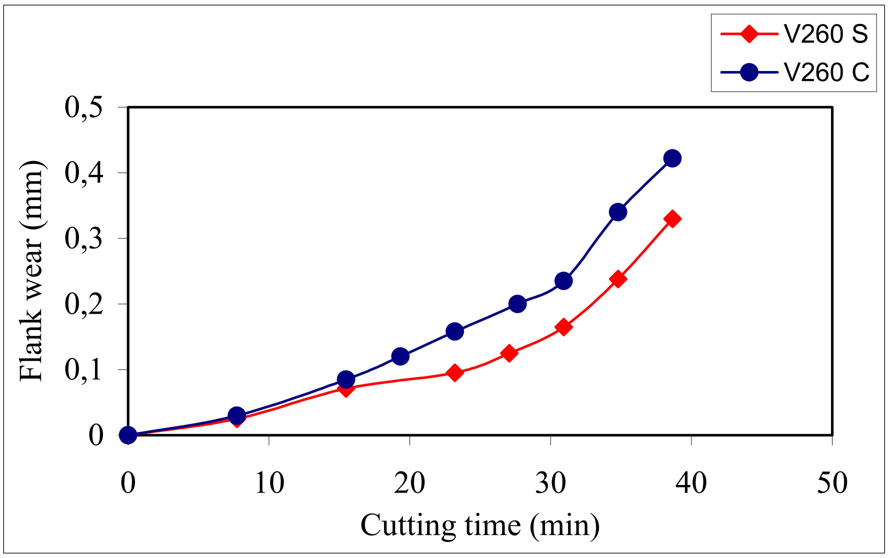


(b)

Figure 3.18: Tool wear vs. cutting time for stable and chatter conditions and cutting speeds for L=110 mm



(a)



(b)

Figure 3.19: Tool wear vs. cutting time for stable and chatter conditions and cutting speeds for L=120 mm

The wear data collected while the cutting tests are shown in Table 3.3. The results are drawn in different forms to demonstrate the dynamic effects on chatter in a better way. Figure 3.18 shows the progress of the tool wear with cutting time for shorter holder length of 110 mm and for cutting speeds of 170 and 260 m/min. In both of two graphs, two curves are shown corresponding to stable and chatter conditions. The same results are presented for 120 mm holder length in Figure 3.19.

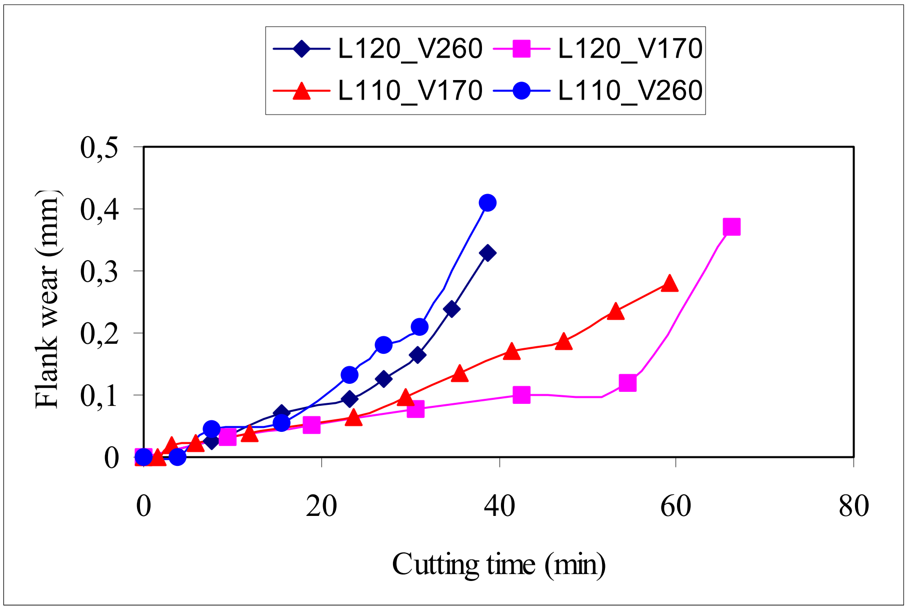
Test no	Chatter condition	Tool life (min)
1	S	49
2	S	30
3	C	30
4	C	16
5	S	56
6	S	33
7	C	41
8	C	27
9*	S	46
10*	C	31
11*	SC	15

Table 3.3: Results of milling tests (* for titanium)

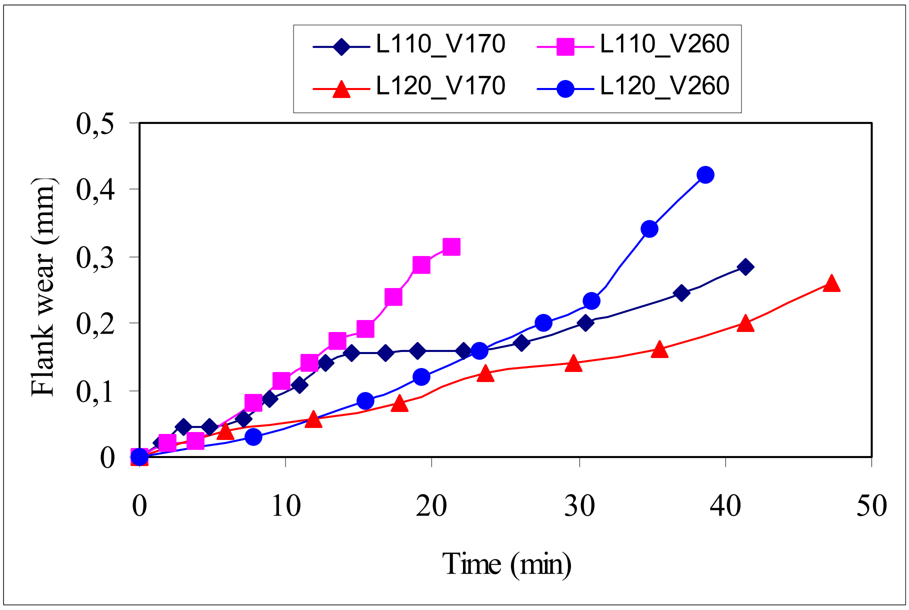
The graphs show that chatter has a dominant effect on tool wear in milling. The rate of the tool wear increases under chatter conditions compared to stable cutting. The effect of chatter on tool life is pronounced but it becomes less descent for higher speeds. That means the effect of chatter at higher cutting speeds is not as much as the effect of chatter at lower speeds.

The reduction in tool life due to chatter is much higher for the low stiffer cases (L=120 mm). That means, the tool life in presence of chatter with a longer tool improves a little according to a shorter tool. This results show the effect of tool rigidity on tool life. The reason for that effect of tool stiffness on tool life can be explained by the mechanism of tool wear. The elasticity of the tool increases as the length of it increases. That means the tool becomes less stiffer when it is long and it becomes more tolerant to any force or impact against it. The less stiffer cutting tool, the more ability to compassionate the poundings of the cutting edge and the impacts of the cutting flute when it is entering into the workpiece material. A cutting tool with higher stiffness would be tougher against the forces and impacts during the interaction with the workpiece material and it would be more fragile. The stiffer tool could cause more microscopic chippings on the cutting edge, thus early tool wear.

The tool life reduction at lower cutting speed (V=170 m/min) for shorter tool due to chatter is about 39% when the same value is 27% for the longer tool. The reduction in tool life at higher cutting speed (V=260 m/min) for the shorter tool due to chatter is nearly 47% when the same value is 19% for the longer tool. At higher cutting speed, the reduction in tool life that depends on the rigidity of the tool increases.



(a)



(b)

Figure 3.20: Comparison of stable (a) and chatter (b) conditions for different tool lengths

The development of the flank wear, for different cutting speeds and tool rigidities for both stable and chatter conditions, is shown in Figure 3.20. The tool wear rates at stable condition are similar for both tool lengths until 0.05 mm flank wear. That time corresponds to first 12 minutes of cutting operation. Similar effect is seen for chatter condition, too. The wear rates at chatter condition for all conditions are the same until 0.04 mm flank wear. That corresponds to machining time about 5 minutes.

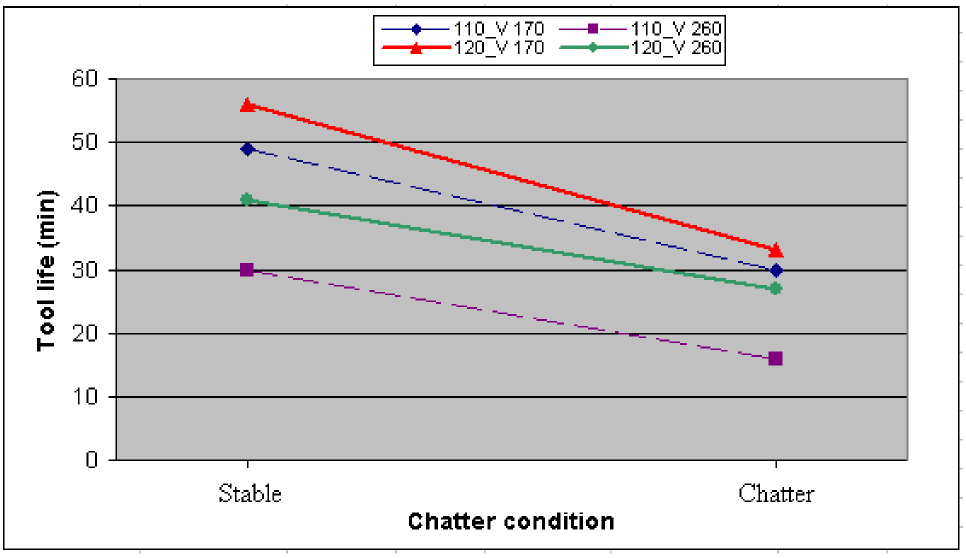


Figure 3.21: Tool life for different chatter conditions

The test results for machining steel are summarized in Figure 3.21. This graph shows that the tool life is reduced up to 47% and in average 32% due to chatter. This result leads a major increase in tool wear and tool cost due to chatter in milling.

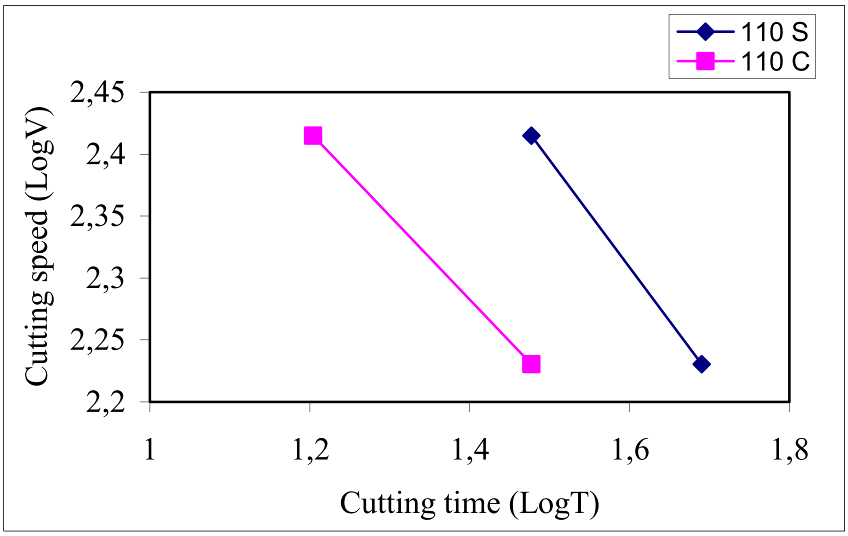


Figure 3.22: Cutting time vs. speed for L=110 mm

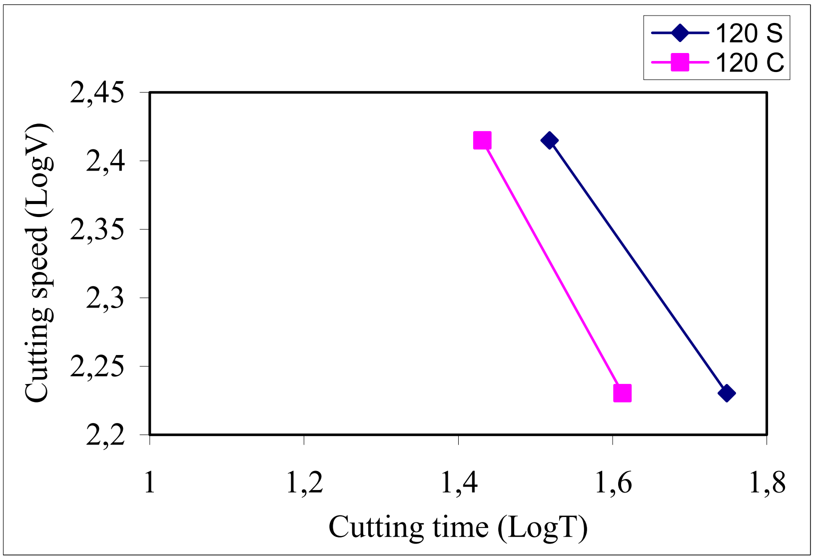


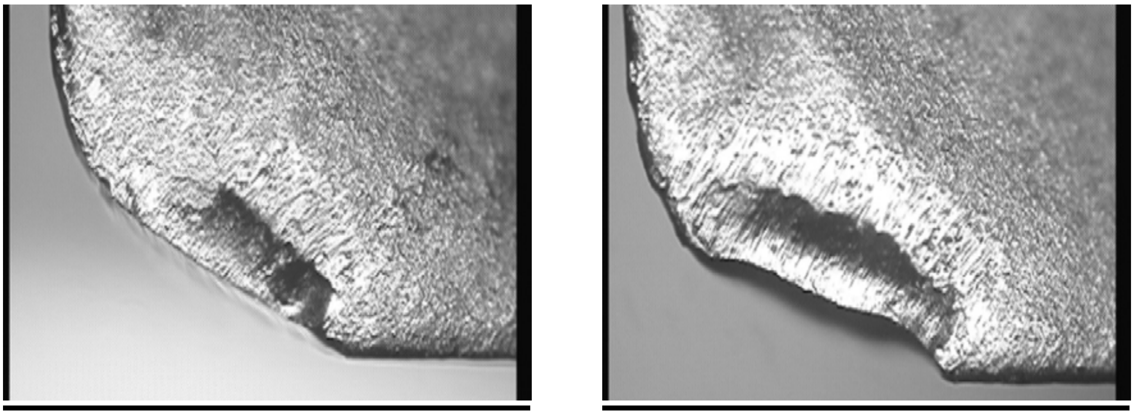
Figure 3.23: Cutting time vs. speed for L=120 mm

Figures 3.22 and 3.23 demonstrate the logarithmic tool life curves. The negative inverse of the slope of these curves is the exponent *n* in Taylor tool life equation. If these two graphs are compared, it can be seen that the variation in tool life at stable condition for two different tool lengths is more regular and the slopes are very similar to each other. The same result is not valid for chatter condition because the variation between tool life at chatter condition for different tool rigidities is much higher and irregular. That difference of chatter condition is more obvious at higher cutting speeds.

	L=110 mm		L=120 mm	
	S	C	S	C
C	3.6942	3.2289	3.635	3.8708
n	0.866	0.675	0.803	1.017

Table 3.4: C and n values identified from wear data in milling tests

The graph of development of the tool wear while machining titanium for one cutting speeds, 35 m/min, and one tool holder lengths, 120 mm, is shown in Figure 3.25. All of titanium tests are done for three different cutting conditions, stable, chatter and severe chatter.



(a) (b)

Figure 24: Worn tools after T6 and T8

The effects of chatter vibrations on tool life in milling are shown in Figure 3.24. These two inserts wear out under the same cutting parameters (L=120 mm and V=260 m/min). Figure 3.24 (a) is the insert of T6 after 38 minutes and Figure 3.24 (b) is the insert of T8 after 38 minutes. The crater wear zone and depth of the crater wear under chatter vibration are obviously greater than the results of stable cutting condition.

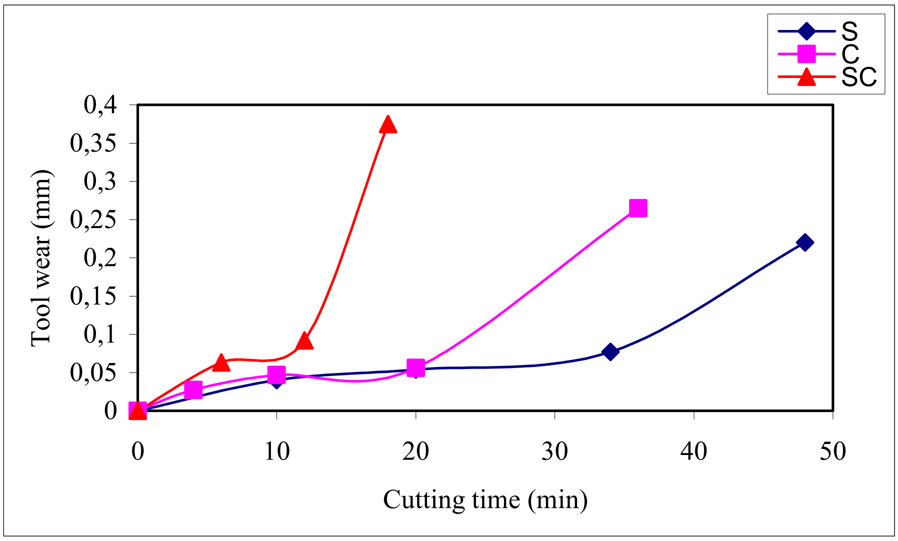


Figure 3.25: Tool wear vs. cutting time for stable, chatter and severe chatter conditions and cutting speeds for titanium

Figure 3.25 clearly shows that chatter has a significant effect on tool wear in milling for titanium, too. The rate of the tool wear increases under chatter condition compared to stable cutting, and under severe chatter condition compared to both, stable and chatter cutting. The tool life is reduced up to 33% under chatter and 67% due to severe chatter. The reduction in tool life is vital under both chatter severities.

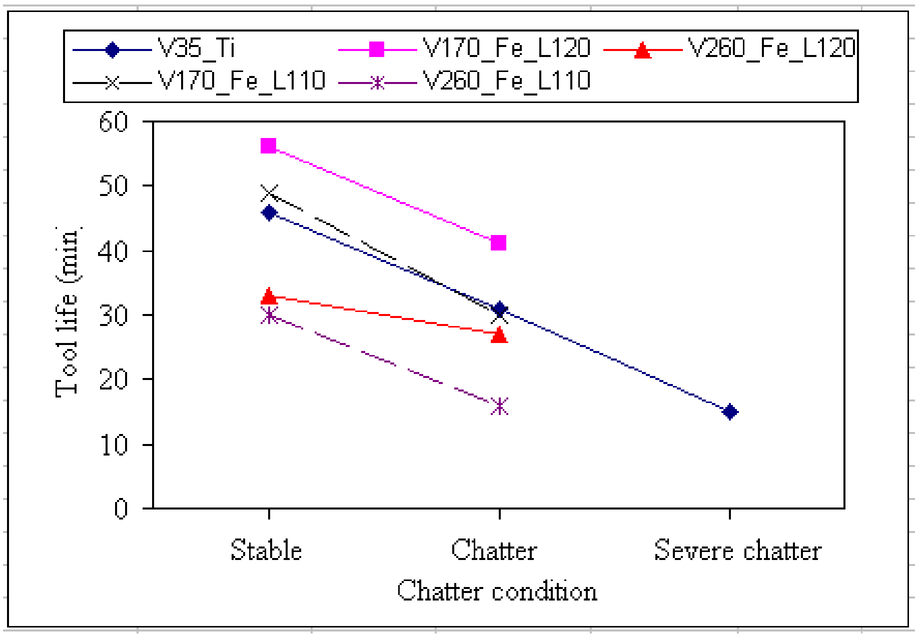


Figure 3.26: Tool life for different chatter conditions for steel and titanium

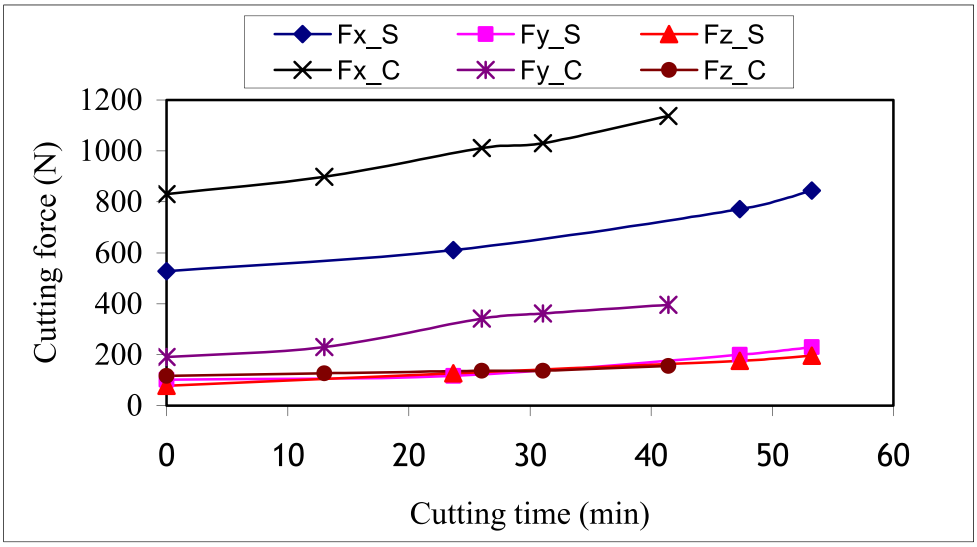
3.2.2 Cutting Forces

The cutting forces are measured in every direction for many times throughout the total cutting time of the tool. The time interval between two cutting force measurements varies between 4 and 23 minutes. That time interval depends on the cutting speed and chatter condition.

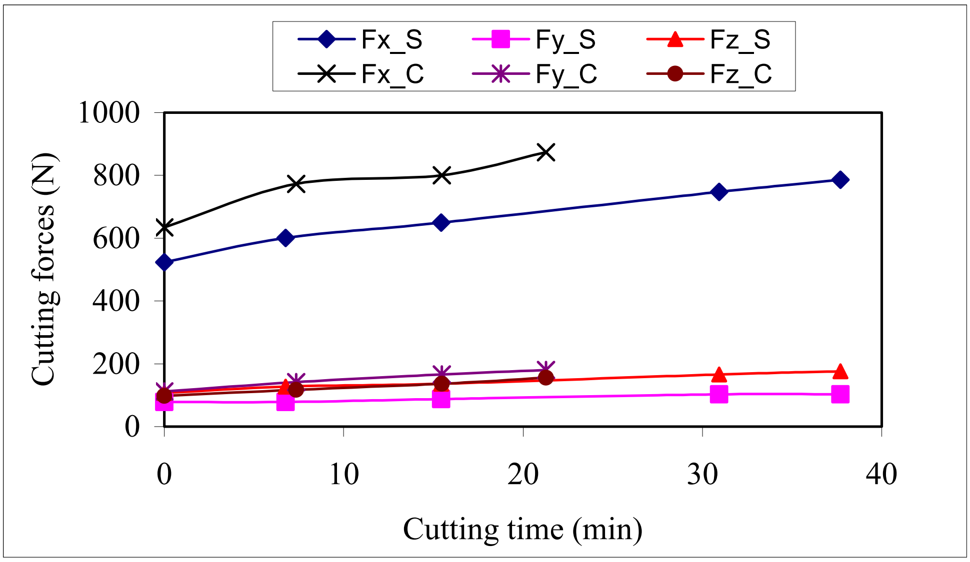
All the cutting forces increase during the cutting process due to wear. The contact area on tool enlarges as the tool wears and that leads to the increase of cutting forces. Another reason can be the deviation in the coefficient of friction as the tool wears. The cutting force in the feed direction, F_x, is analyzed in comparison. The cutting forces at higher speeds are less than the forces at lower speeds. The behavior of cutting forces against cutting speed is not always the same and it depends on the material, machining process and many other parameters. The reason for the increase in cutting forces can be the increase of the cutting temperature at higher speeds.

The cutting force difference between stable and chatter conditions is evident. The feed force difference between two dynamic conditions for lower cutting speed (V=170 m/min) is nearly 60% for high rigid tool (L=110 mm) as shown in Figure 3.27 (a) and 40% for less rigid tool (L=120 mm) as shown in Figure 3.28 (a).

The cutting forces and their development by the cutting time for stable and chatter conditions and different tool lengths are shown in Figures 3.27 and 3.28.



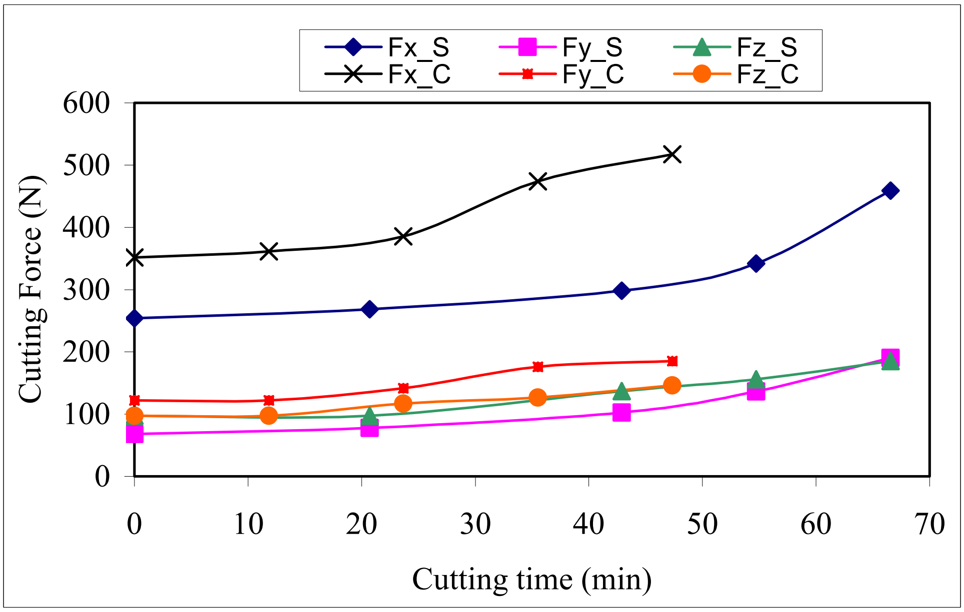
(a)



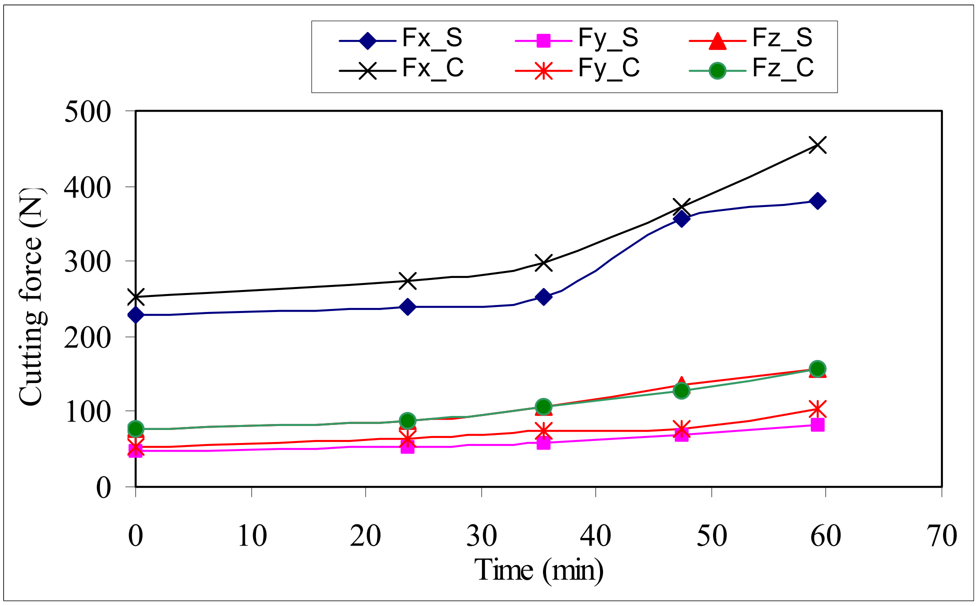
(b)

Figure 3.27: Peak cutting forces for V=170 m/min (a) and V=260 m/min (b) for L=110 mm

The cutting force difference between stable and chatter conditions decreases at higher speeds due to the general decrease at all forces. Plus, the differences between two cutting conditions are very small for the tangential forces, F_z and they could be neglected.



(a)



(b)

Figure 3.28: Peak cutting forces for V=170 m/min (a) and V=260 m/min (b) for L=120 mm

The same cutting force behaviors can be observed for the longer tool, too. There is not much difference between F_y and F_z forces in stable and chatter conditions for both cutting speeds. There is nearly no difference for higher cutting speeds for L=120 mm as shown in Figure 3.28 (b).

The chatter frequencies are determined by using a microphone setup. The chatter frequency for L=120 mm is about 631 Hz. The frequency of the tool is 725 Hz and chatter frequency is generally higher than the modal frequency. But in some milling cases, lower chatter frequencies can be encountered as well. The chatter frequency and the sound data are shown in Figure 3.29.

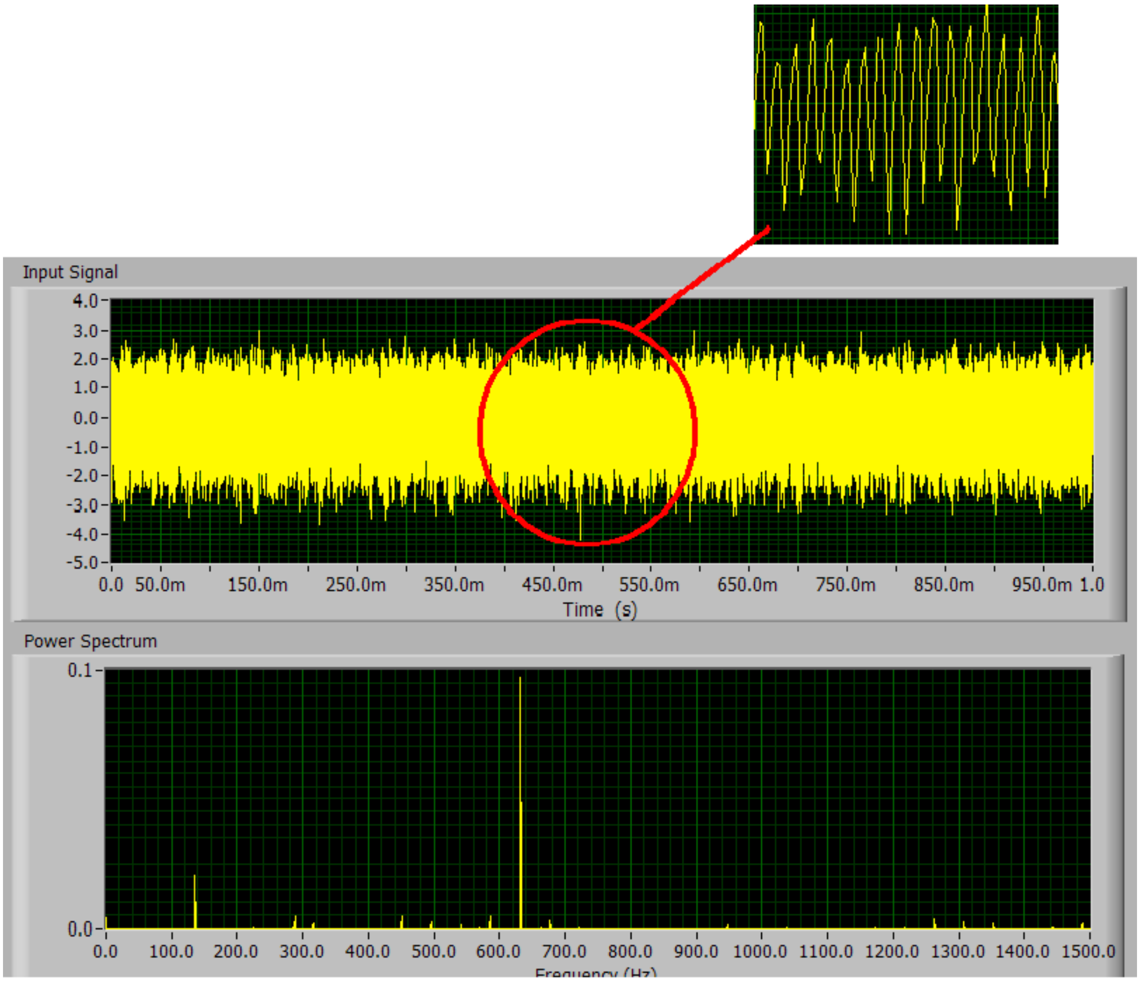
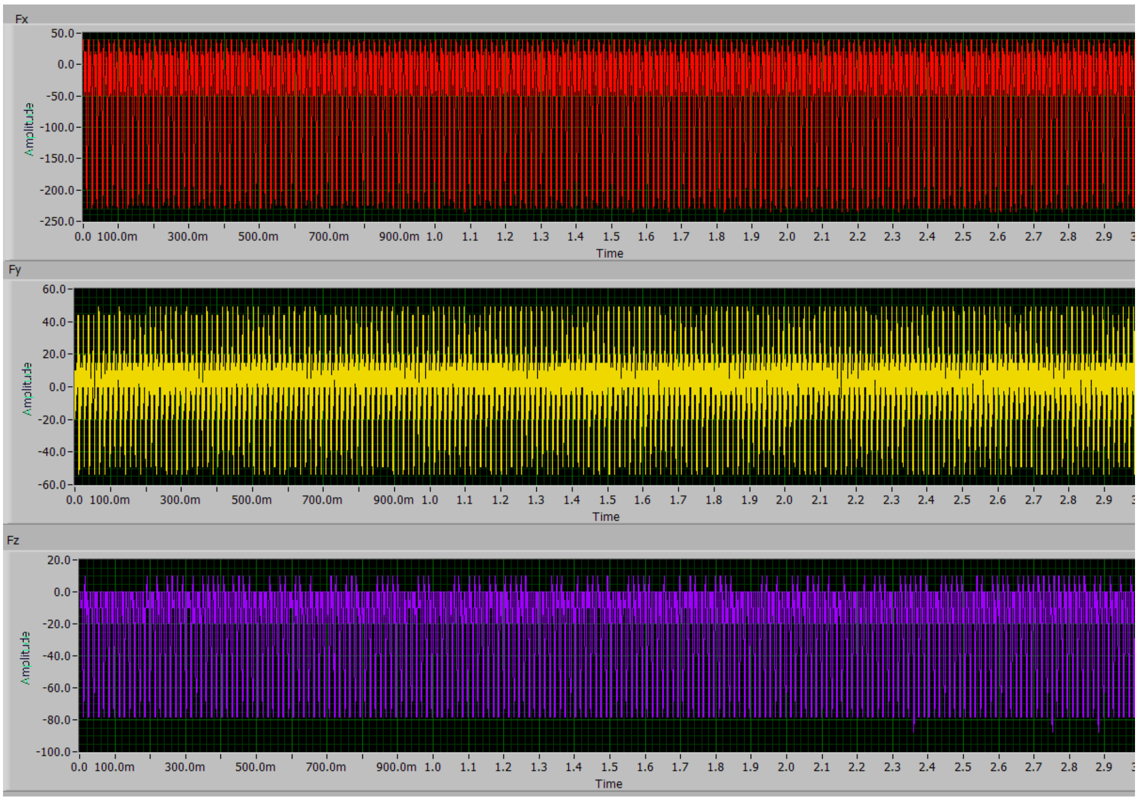
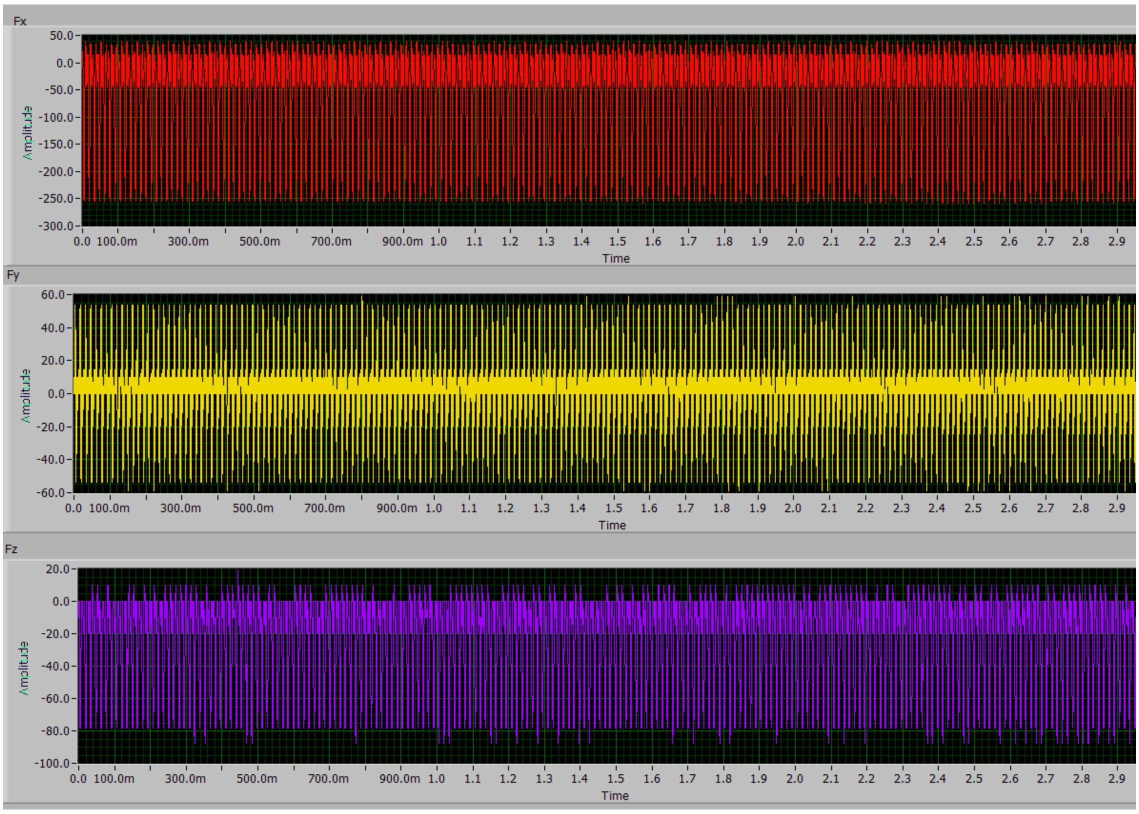


Figure 3.29: Chatter frequency for L=120 mm

The output of the data acquisition software which collects the milling force data is shown in Figure 3.30. The sampling rate for these measurements is 10000 points per second.



(a)



(b)

Figure 3.30: Milling forces for T6 (a) and T8 (b) at first minute

Distance (m)	Time (min)	F_x (N)	F_y (N)	F_z (N)
V=170 m/min, Stable				
0	0	527.2	102.2	78.1
6.4	23.67	610.4	117.2	127
12.8	47.33	771.5	200.2	175.8
14.4	53.25	844.7	229.5	195.4
V=260 m/min, Stable				
0	0	523.7	78.1	107.4
2.8	6.76	600.6	78.2	127
6.4	15.44	649.4	88	136.7
12.8	30.94	747	102.5	166
15.6	37.7	786.1	102.5	175.8
V=170 m/min, Chatter				
0	0	830	190.4	117.2
3.52	13.02	898	229.6	126.9
7.04	26.03	1011	341.8	136.8
8.4	31.06	1030.2	361.4	137
11.2	41.42	1137.8	395.2	156.3
V=260 m/min, Chatter				
0	0	634.8	112.3	97.6
3.04	7.35	772.5	141.6	117.2
6.4	15.47	800.8	166	136.7
8.8	21.27	874	180.6	156.3

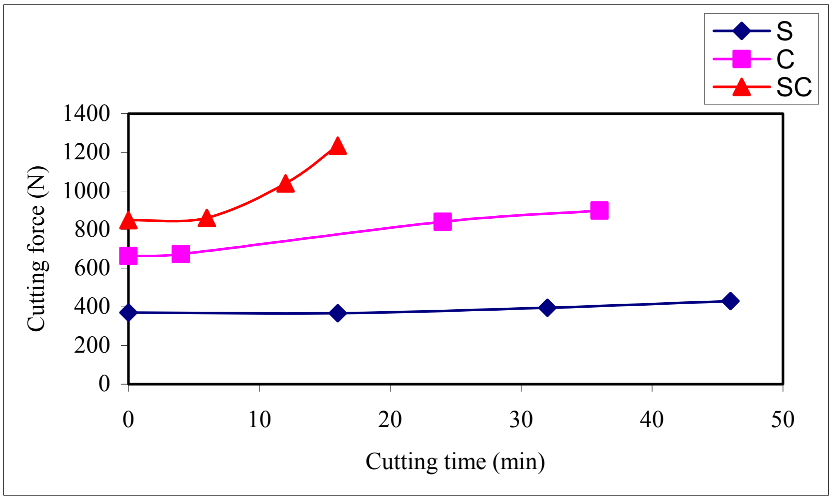
Table 3.5: Detailed milling forces for steel at L=110 mm

Tables 3.5 and 3.6 show the cutting force data of steel for all cutting conditions (different tool lengths, cutting speeds and chatter conditions) in detail. Cutting time, cutting distance of the measured force and three cutting forces (F_x for feed force, F_y for radial force and F_z for tangential force) are given. The general decrease in cutting forces as cutting speed increases and the effect of chatter on cutting forces can be seen in Tables 3.5 and 3.6, too.

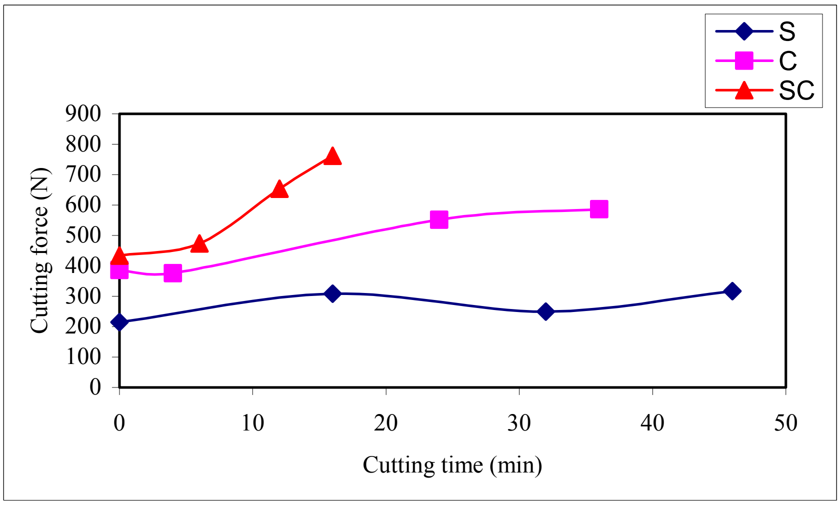
Distance (m)	Time (min)	F_x (N)	F_y (N)	F_z (N)
V=170 m/min, Stable				
0	0	254	68.4	97.6
5.6	20.71	268.6	78.1	97.6
11.6	42.9	298	102.6	136.8
14.8	54.73	341.8	136.7	156.2
18	66.56	459	190.5	185.4
V=260 m/min, Stable				
0	0	229.5	48.8	78.1
6.4	23.66	239.3	53.7	87.9
9.6	35.5	253.9	58.6	107.5
12.8	47.34	356.4	68.4	136.7
16	59.17	380.8	83	156.2
V=170 m/min, Chatter				
0	0	351.4	122	97.6
3.2	11.83	361.3	122.1	97.7
6.4	23.67	385.7	141.6	117.2
9.6	35.5	473.6	175.8	127
12.8	47.34	517.5	185.5	146.5
V=260 m/min, Chatter				
0	0	253.9	53.7	78.1
6.4	23.66	273.4	63.5	87.9
9.6	35.5	297.9	73.2	107.4
12.8	47.34	371.1	78.2	127
16	59.17	454	102.6	156.2

Table 3.6: Detailed milling forces for steel at L=120 mm

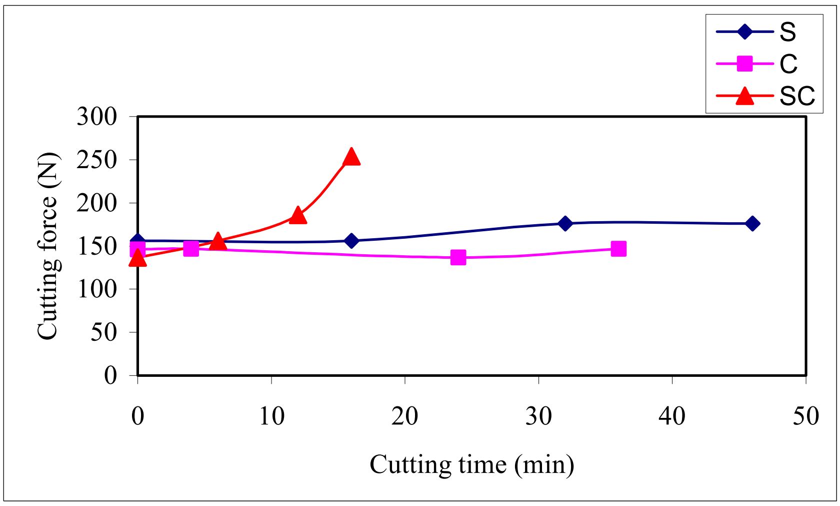
The cutting force data are presented in Table 3.7 for titanium tests. It is easily seen that the chatter vibrations generally increase cutting forces. This result is more obvious in the feed force (F_x). The increase of cutting forces is directly proportional with the severity of chatter vibration. The chatter (C) condition increases F_x about max. 79% and the severe chatter (SC) condition increases F_x about max. 128% according to the stable (S) condition.



(a)

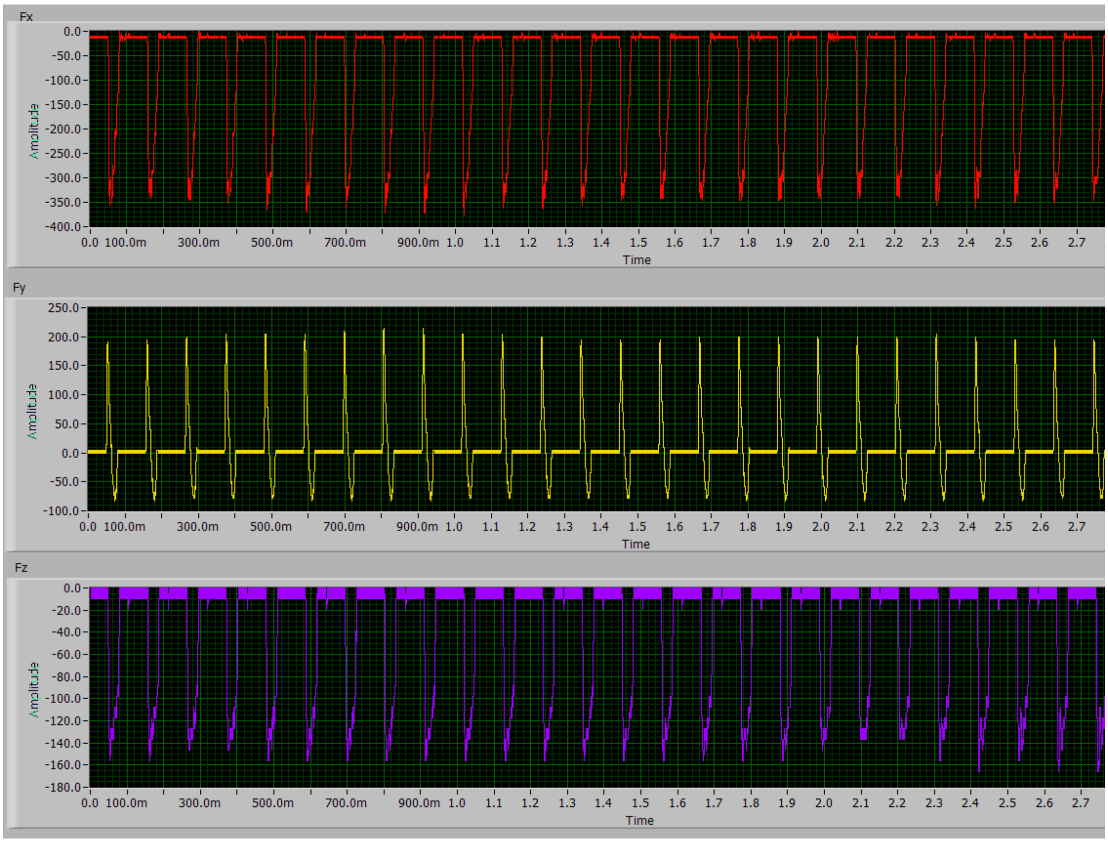


(b)

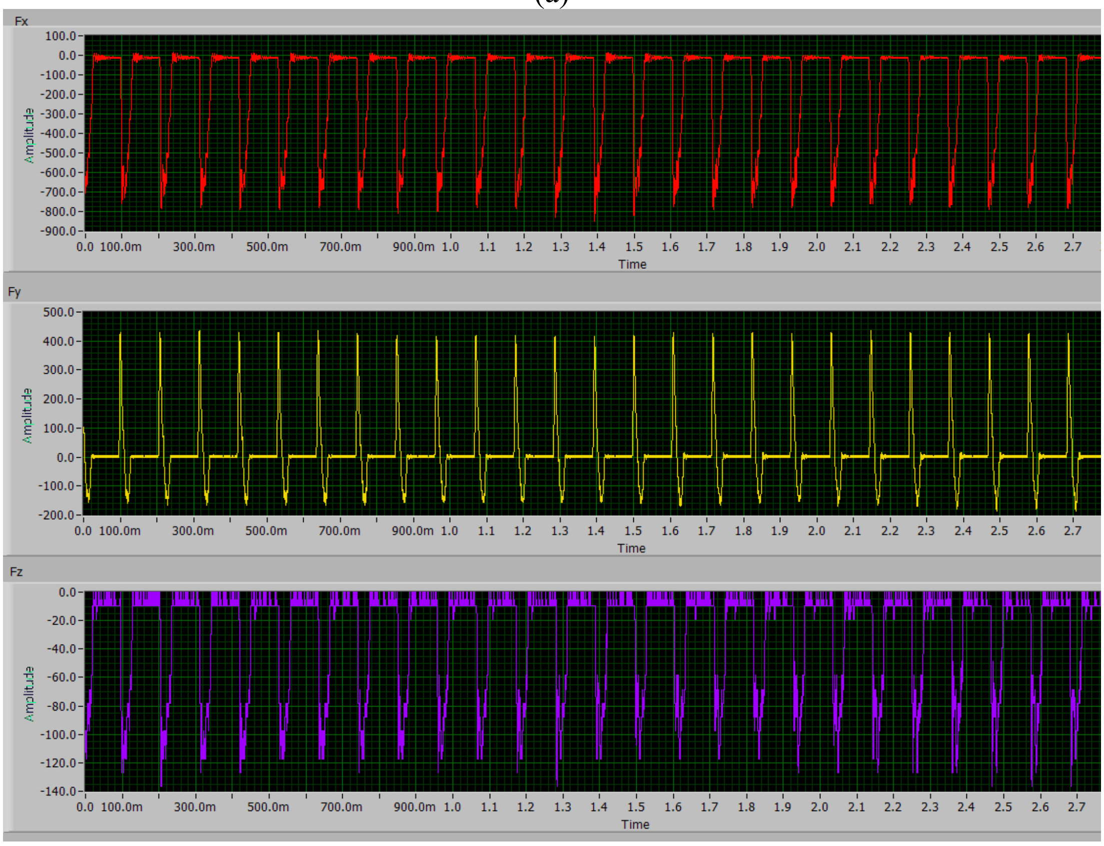


(c)

Figure 3.31: Peak cutting forces, F_x (a), F_y (b) and F_z (c), of titanium tests for L=120 mm



(a)



(b)

Figure 3.32: Milling forces for T9 (a) and T11 (b) at first minute for titanium

Distance (m)	Time (min)	F_x (N)	F_y (N)	F_z (N)
Stable				
0	0	371	215	156
0.83	16	368	308	156
1.66	32	396	249	176
2.39	46	430	317	176
Chatter				
0	0	664	386	146
0.21	4	674	376	147
1.25	24	840	552	137
1.87	36	898	586	147
Severe chatter				
0	0	849	434	137
0.31	6	860	474	156
0.62	12	1040	654	186
0.83	16	1235	762	254

Table 3.7: Detailed milling forces for titanium

3.2.3 Summary of Milling Tests

It is clearly seen in the milling tests that chatter vibration increases tool wear. The tool life decreases about 30% to 50% under chatter conditions in milling tests of AISI 1040 steel. Similar effect of chatter condition can be observed in titanium tests, too. The tool life is reduced up to 33% under chatter and 67% due to severe chatter in milling tests of titanium. The reduction in tool life is significant under both, chatter and severe chatter conditions. The cutting forces are affected by chatter, too. The feed force while cutting steel, increases about 40% to 60% under chatter as shown in Figure 3.27 (a) and 3.28 (a) . The feed force increases under chatter and severe chatter vibrations up to 130% while cutting titanium.

CHAPTER 4

DISCUSSION

The results of turning and milling tests with different workpiece materials and under different cutting conditions are presented in chapter 3. The tool wear, vibration amplitude and force data which obtained from the cutting tests are given and demonstrated as figures and tables. This chapter is a paraphrase of chapter 3. The reasons of the results of turning and milling tests are explained and discussed.

4.1 Turning

4.1.1 Effect of Cutting Speed

Different cutting speeds are used in the tests to see the effect of speed on tool life and other parameters. Three different cutting speeds, 170, 110 and 50 m/min, are used in turning tests. Table 3.1 clearly gives the comparison of the cutting speed and tool life. This table shows that the tool life is reduced more than 40% and up to 65% for stable cutting condition, about 85% for chatter condition and, more than 60% and up to 90% for severe chatter condition when the cutting speed is increased up to 110 m/min and 170 m/min, respectively. Doubling of cutting speed, 50 m/min, leads an increase in tool life about 70% in average. Tripling of cutting speed, 50 m/min, reduces tool life about %88 in average. Figures 3.3 and 3.4 support that conclusion. These results show that tool wear rate is directly proportional to the cutting speed. It is clear that effect of cutting speed is very vital on tool life. Higher cutting speeds mean less production time but it also brings extra cost for tooling and longer setup time.

The main reason of the reduction of the tool life due to the increase of cutting speed is temperature. It is generally known that cutting temperature increases as the cutting speed increases. Trent et al. [2] showed that the surface temperature of the cutting insert while cutting of very low carbon steel at 91 m/min is about 650 ^{0}C and the temperature of the surface of the insert is about 900 ^{0}C at 213 m/min. Another parameter that increases cutting temperature in turning is the mechanics of turning operations. Turning is a continuous cutting and there is always a contact between the tool edge and the workpiece material as the cutting proceeds. The increase in cutting temperature leads faster tool wear and failure.

The tool wear rate under vibration depends on the cutting speed, too. There is not much difference between tool life curves of chatter condition and severe chatter conditions at higher cutting speeds (V=170 m/min). The difference between two chatter conditions becomes clear as the cutting speed decreases. And also, higher cutting speeds increase the effect of chatter vibrations on tool life.

The tool life data in Figures 3.1 and 3.2 give important clues about the effect of cutting speed. The tool wear rate increases at higher cutting speeds. That is acceptable because of the decrease in tool life in the same condition. The effects of chatter vibrations are also more significant at higher cutting speeds.

4.1.2 Effect of Chatter

The main purpose of this study is to understand the effect of chatter vibrations on tool life so different severities of chatter are applied in turning. Turning tests are done under three dynamic conditions: stable, chatter and severe chatter. The tests results show that chatter vibrations have substantial negative effects on tool life. Tool wear data and the reduction in tool life due to chatter are given in Table 3.1. This table shows that the tool life is reduced about 60-80%. The decrease in tool life for severe chatter is much more. Tool life reduces about 60-70% for shorter tool holder and 60-90% for longer tool holder under severe chatter.

The effect of chatter also depends on the cutting speed. Figures 3.1 and 3.2 show that higher cutting speeds make chatter vibrations more effective on tool life. But the effects of chatter and severe chatter conditions on tool life are nearly the same for higher cutting speeds (V=170 m/min) and the wear rates are very similar as shown in Figure 3.6. The difference between the effects of chatter and severe chatter on tool life appears especially lower cutting speeds (V=50 m/min). The effects of chatter vibrations on tool life also depend on the tool rigidity. Less stiffer tool holders set off the effect of chatter vibration. Comparison of Figures 3.6 and 3.7 clarifies that result.

4.1.3 Effect of Vibration Amplitude

Vibration amplitudes in the range of 5 μm to 25 μm are measured in the turning tests. Figure 3.12 shows the amplitudes in chatter and severe chatter conditions. The slopes of lines for the same tool holder lengths are similar. The amplitude variation for less rigid tool holder is much higher than the variation of the more rigid tool holder. That results show that variation rate of the amplitudes under different chatter conditions depends on tool stiffness. The stiffer tool means less variation in vibration amplitudes between chatter and severe chatter.

Figure 3.13 shows the effects of the chatter vibration amplitudes on tool life. The most significant variation in both, tool life and vibration amplitude, is observed at the test with the parameters, L=135 mm and V=50 m/min.

4.1.4 Effect of Tool Length

The variation of length changes the stiffness of the tool holder. It is seen in the turning tests that the tool holder length affects tool life under chatter vibrations. That effect is dominant for severe chatter conditions. The cutting distances under severe chatter decrease about 2% for V=50 m/min, 135% for V=110 m/min and 13% for V=170 m/min when tool holder length is increased from 110 mm to 135 mm according to Figure 3.5. That means tool life decreases when the rigidity of tool decreases under chatter conditions. The less rigidity of the tool means higher vibration amplitudes under chatter vibration in turning. Higher amplitudes create impacts of the cutting edge to the surface of the workpiece and that situation accelerates tool wear.

The results of the effects of tool rigidity on tool life are not the same under stable conditions. The tool life of the less stiff tool holder is longer than the tool life of the stiffer one. That results can lead us to a conclusion. The effect of the tool holder length on tool life depends on the dynamic condition of cutting process. If there is chatter in the process then the tool life decreases as the tool holder length increases, due to existence of vibration in turning.

4.2 Milling

4.2.1 The Effect of Cutting Speed

Two different cutting speeds are used in the milling tests to observe the effect of cutting speed on tool life. Various cutting speeds, 35, 170, 260 m/min, are used in milling tests for steel and titanium. Table 3.3 shows tool life for all milling tests. The tool life is reduced about 40% for stable conditions and up to 46% for chatter conditions when the cutting speed is increased from 170 m/min up to 260 m/min. The cutting speed has a vital effect on tool life in milling, too. Figures, 3.18, 3.19 and 3.20 clearly show that effect. The tool wear rates for both cutting speeds and both chatter conditions are very similar in the early stages of wear development.

The increase in the cutting zone temperature due to the increase in cutting speed is the main reason for the decrease on tool life, again. The mechanics of milling process is different from turning and it is a discontinuous cutting process. That means there are short time spaces between every revolution of the cutting tool. That time spaces are much longer when cutting speed is smaller. So, that situation creates extra time for the cutting tool to cool down.

The cutting forces are very important to manufacturing engineers in machining. They are always desired to be smaller. The cutting forces decrease as the cutting speed increases in milling tests of both, steel and titanium. There can be several reasons for that. The specific cutting energy decreases as the cutting speed increases, so the reduction in specific cutting energy leads a diminishing in cutting forces. Another reason can be the effect of cutting zone temperature. As the cutting speed increases, the temperature increases, too. That high temperature reduces the shear strength. Less shear strength in the flow zone leads to an increase of seizure region and that results easier chip flow mechanism. That effect decreases the cutting forces [1].

4.2.2 Effect of Chatter

Milling tests for AISI 1040 steel are done under two dynamic cutting conditions, stable and chatter. Milling tests for titanium are done under three dynamic conditions, stable, chatter and severe chatter. Table 3.3 shows the tool life for different chatter conditions. The tool life decreases about 40-50% for high rigid tool and 20-30% for low rigid tool due to chatter in steel tests. The reduction on tool life is about 35% for chatter condition and 70% for severe chatter condition in titanium tests. The results of different two materials clear that mild chatter usually decreases tool life about 30-40%. That decrease in tool life is very vital for machining requirements and production costs.

The effect of chatter condition can be seen in Figure 3.26. The general slope of the decrease in tool life is regular and similar. This generalization shows that the effects of chatter vibrations on tool life have a mechanism and they are not random or irregular.

The cutting forces under chatter vibration are more than the cutting forces under stable condition. That difference between the feed force components of two cutting conditions reaches up to 60% for machining of steel. That difference is more in machining of titanium. The difference between stable and chatter feed forces is 80% for chatter condition and more than 100% for severe chatter condition. There can be several reason for the increase of cutting forces under chatter vibration. The cutting edge of the tool is not static while chatter and it vibrates. That vibration leads the cutting edge to impact to the workpiece material. These impacts can create additional forces on tool and cutting edge, and cause micro chipping on the cutting edge of the insert. It is commonly known that worn cutting tools increase cutting forces. In addition, as the tool wears, the area of contact is increased and that leads to an increase in the cutting forces. Also, due to wear the coefficient of friction is increased which results in higher cutting force produced during the machining.

4.2.3 Effect of Tool Length

The length of the cutting tool outside of the tool holder has also an effect on tool life in milling. The stiffness and rigidity of the tool increase as the length of it decreases. The effects of chatter vibrations on tool life for less stiff tool are not as much as the effects of chatter on tool life for high stiff tool. That means longer cutting tool provides longer tool life. That situation is valid for both, stable and chatter conditions in milling. Tool life with usage of longer cutting tool improves about 15%. That increase on tool life cannot be disregarded. The tool life improves under chatter condition in milling, too. But it is important to notice that, the improvement of tool life under chatter in milling depends on the severity of chatter vibrations. Higher tool length causes more chatter for the same depth of cut and the severity of chatter would start to decrease tool life after a specific length and tool lengths above that specific point would decrease tool life. So, total amount of increase on the tool life by the variation of the tool length under chatter conditions cannot be related to cutting tool stiffness.

Tool life decreases more in the tests with less stiff tools. The effect of tool stiffness on tool life can be related to tool wear. The body of the tool becomes more elastic when it is longer. That elasticity and low stiffness bring a permissive structure to the cutting tool, so the cutting edge of the tool behaves just like a ductile material. Less stiff cutting tool edge is more tolerant to the forces and impacts while cutting metal. The stiffness of the cutting tool prevents the cutting edge against micro chippings and deep impacts. That conservation makes tool life longer.

4.2.4 Wear Effects for Different Materials

Two different workpiece materials were used in milling tests. These are mild steel, AISI 1040, which is commonly used in general manufacturing and titanium alloy, $TiAl_6V_4$, which is one of the main demands of aerospace industry. These materials are especially selected, so the results and the data of this study can be useful in manufacturing. It is not easy to compare steel and titanium after cutting tests due to the different cutting conditions and parameters. Titanium is machined at V=35 m/min in milling tests due to the machining requirements and this speed is 1/5 of the minimum cutting speed for steel. Also, the titanium tests are done under wet cutting conditions which increases tool life. But it is clear that chatter has similar effects on tool life for titanium, too. After both, steel and titanium tests, it is clear that chatter decreases tool life about 30-40%. Titanium tests support that conclusion.

There are also some relationships between the results of two materials. The cutting forces show some similarities in Figures 3.27 and 3.31. The force differences between chatter condition and stable condition are generally increase as the cutting proceeds. The cutting forces in titanium tests are relatively higher than steel tests in some conditions. The benchmark of Figures 3.28 and 3.31 shows that in some cases, cutting forces of titanium under stable conditions are higher than the cutting forces of steel under chatter conditions for the same tool length. The main reason for that is the material characteristic of titanium.

CHAPTER 5

CONCLUSIONS

The aim of our investigation is to understand the influence of chatter instability on tool life with combining different cutting parameters, cutting processes and tool rigidities. Vibration amplitudes and corresponding cutting forces in three directions are measured during the cutting test. Tool wear development is observed at varying time intervals and *VB*=0.2 mm is considered as criterion of tool life to shorten the experimental time.

Based on the results obtained from the cutting tests, some conclusions are cited herewith:

- Chatter vibrations lead a vital reduction in tool life about 50% for most of the cases and more than 80 % in some cases (higher cutting speeds) in turning tests. Tool life decreases about 30-50% under chatter and 70% under severe chatter conditions in milling.

- The effects of chatter on tool life are more pronounced at higher cutting speeds in turning.

- Vibration amplitude has direct influence on tool life. Higher the vibration amplitude, lower the tool life is. The vibration amplitudes are increased in low-rigid-tool as expected. The difference between variation of amplitudes when high-rigid and low-rigid tools are compared, is much higher at higher cutting speeds in turning.

- Chatter results in surface finish nearly two times worse than stable cutting. That poor surface finish and deviations in the dimensional accuracy will cause additional operations which will bring extra cost to manufacturing.

- The rigidity of the cutting system has strong influence on tool life. At stable cutting conditions less rigid tool holder results in higher tool life in turning. The tool life increases as the tool rigidity decreases. The reduction in tool life due to tool rigidity increases at higher cutting speed

- There are significant cutting force differences between stable and chatter conditions. F_x difference between these conditions is about 60% for the tool with high rigidity and 40% for the tool with less rigidity in milling.

- The development of the tool wear under chatter is faster than stable condition. But the effect of chatter intensity is less significant at higher speeds in milling.

As a future work, these tests would have performed for different cutting parameters and conditions. The parameters which decisively influence the test results like cutting speed, feed rate, cutting tool material and geometry, workpiece material, cutting direction and type, and cutting conditions (dry or wet cutting, 3-axis or 5-axis machining), etc. could be tried with many different combinations. The results which are obtained from these long tests will be used to create a database which could be the basis for a commercial software. That software can be integrated into CAD/CAM systems to develop the optimum machining parameters for industrial applications.

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