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Regenerative chatter Phenomenon in the Turning Process based on the alloy steels 1020, 1035 and 1045

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Abstract : Regenerative vibration is a major drawback in machining processes reducing the geometric accuracy and dynamic stability of the cutting system. Achieving a dynamically stable cutting operation represents a significant decrease in the production time and therefore in the costs associated with this process. The information provided by the stability lobe diagrams is of great importance, since from them we know the range of spindle rotation speeds and chip thicknesses at which the cutting operation takes place in a state free from the phenomenon of regenerative chatter, avoiding the rapid wear of the cutting tool and achieving quality surface finishes.

In the present investigation, the behavior of the turning operations in steel 1020, steel 1035 and steel 1045 is characterized, with the objective of verifying the presence of instability in the machining caused by the regenerative chattering in the machine tools. Based on the analytical models proposed by Altintas and Budak for the stabilization of self-excited vibrations, a computer tool is developed capable of generating stability lobe diagrams, which allow us to appreciate the operating conditions in which machining presents stable behavior, to simulate the material removal process considering certain parameters specific to the machine tool.
Keywords : turning, regenerative chatter, lobe diagrams.

1. Introduction

The turning process is one of the most important and efficient of the conventional machining processes. Normally the workpiece rotates on a spindle and the cutting tool is inserted axially, radially or in both directions simultaneously to achieve the required surface area. During the cutting process three different mechanical vibrations can occur because the mounting of the elements within a machining system can never

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be completely rigid, these three types of vibrations are known as free vibrations, forced vibrations and self-excited vibrations. The tendency of different structures to vibrate at their natural frequencies during machining and the possibility of vibration synchronization leads to chatter vibration, a phenomenon known to be regenerative and associated with many negative effects. The chattering vibration defines the maximum values of the cutting parameters and therefore operates as a limiting factor for the production settings[1].

Machine tool chatter is a state of instability that commonly occurs in machining processes involving stock removal. This phenomenon has been characterized as a problem that negatively affects the integrity of the machine, the quality of the surface and the dimensional accuracy of the final product, in addition to producing excessive wear on the cutting tool. The dynamics of machining along with machine tool vibration has long been under study, however, chatter remains a difficult problem to deal with in the manufacturing industry[2].

To mitigate the phenomenon of chatter, many investigations have been carried out with the purpose of predicting and therefore taking the appropriate measures to avoid it during the machining process. The investigations can be divided into two relevant categories, those dedicated to the analysis of the chatter stability and those oriented to the monitoring and control of the phenomenon[3–7].Appropriate strategies for vibration detection and reduction should be proposed and exploited to ultimately improve the final quality of machined parts. It is well known that the instability of vibrations can be reduced by increasing damping, since the latter has a proportional relationship with the stability limits, Martins da Silva et al. addressed this problem by proposing a methodology for vibration reduction through the use of piezoelectric patches installed in the tool holder and connected to an electrical circuit, which is loaded with the energy dissipation that provides damping to the system[8].

2. Methodology

2.1. Purpose of the software

To study and predict the phenomenon of regenerative trembling in the turning process, an application developed in the MATLAB® software was used, which is based on the methods proposed by Altintas and Budak for the elaboration of stability lobes. To do this, it is necessary to know a group of parameters that are related to some physical properties of the material of the part to be machined, such as the constant of the specific cutting force, and the nature of the cutting tool, such as the natural frequency, the constant of rigidity and the constant of damping. These parameters are the inputs of the user interface and are the ones that govern the performance of the system, which were given as output of the system were stability lobe diagrams on Cartesian axes formed by the spindle rotation speeds and the cutting depth.

2.2. Fundamental equations

The turning operation can be modeled as a one-degree freedom vibratory system, where the excitation function is the shear force, so the plant is said to experience self-excited vibrations, which can be governed by the equation.

$$m_e\ddot{y}(t) + b_e\dot{y}(t) + k_e y(t) = K_c a * [y(t-T) - y(t)], \qquad (1)$$

The right side of the equation being the shear force represented in detail, where K_c is the specific shear force in $[\mathrm{N/m^2}]$, a the depth of cut measured in $[\mathrm{mm^2}]$ and the term $[y(t-T) - y(t)]$ describes the dynamic chip thickness behavior measured in $[\mathrm{m}]$, Figure 1 shows the latter in detail.

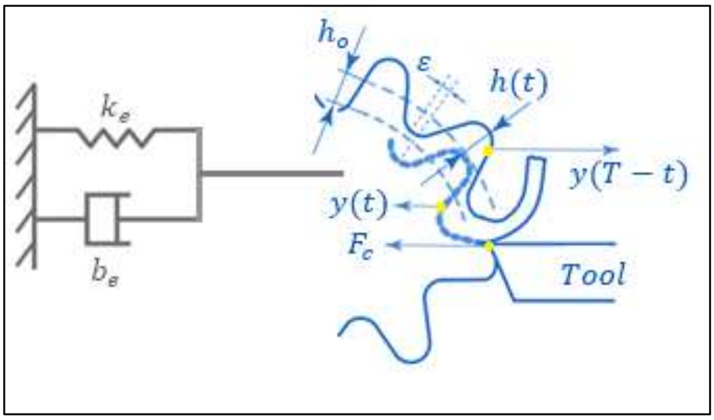

Figure 1.Regenerative re-trembling diagram in orthogonal cut.

Applying the Laplace transform to the equation (1) and assuming initial values equal to zero then results in

$$Y(s) = \frac{1}{m_e s^2 + b_e s + k_e}[K_c a * Y(s)(e^{-sT} - 1)], \quad (2)$$

Where the term $K_c a * Y(s)$ represents the shear force in the frequency domain, then the equation (2) can be rewritten as follows

$$\frac{F_c(s)}{K_c a} = \frac{1}{m_e s^2 + c_e s + k_e} F_c(s)(e^{-sT} - 1), \quad (3)$$

This can be summarized as

$$F_c(s)[1 + K_c a(1 - e^{-sT})\Phi(s)] = 0, \quad (4)$$

since

$$\Phi(s) = \frac{1}{m_e s^2 + c_e s + k_e}. \quad (5)$$

The equation (5) is solved using the method proposed by Budak and Altintas, that is, by making the shear force harmonic and decreasing over time, from which the following expression is obtained

$$F_c(s)e^{-j\omega_c T}[1 + K_c a(1 - e^{-sT})\Phi(s)] = 0. \quad (6)$$

In obtaining the non-trivial equation, the following must be met

$$K_c a(1 - e^{-sT}) = -\frac{1}{\Phi(s)} \quad (7)$$

Expressing the complex variable as $s = \sigma + j\omega_c$. If the real part of the complex variable is positive in the term e^{-sT} of the equation (7), there is an exponential term in the solution in the time domain and the trembling phenomenon grows indefinitely, on the other hand, if the real term is negative, the trembling is eliminated, and the system becomes stable. Finally, if the real part is zero, i.e. $s = jw_c$, the system is critically stable, and the workpiece oscillates with a constant amplitude at a frequency w_c. Bearing in mind that the vibration frequency of the re-bending is not equal to the natural frequency of the structure, because the characteristic equation of the dynamic cutting process has additional terms beyond the transfer function of the structure. However, the magnitude of the vibration frequency of the trembling remains close to that of the natural frequency of the structure[9]. The interest of this research focuses on the critically stable zone, so the equation (7) is rewritten as

$$\frac{-1}{\Phi(j\omega_c)} = K_c a_{lim}\left(1 - e^{-j\omega_c T}\right), \qquad (8)$$

Where a_{lim} is the highest axial cutting depth for vibration-free, chatter-free machining. Now, using Euler's complex identity and applying it to the equation (8) gives

$$\frac{-1}{\Phi(j\omega_c)} = K_c a_{lim}[1 - \cos(\omega_c T) + j \cdot \sin(\omega_c T)]. \qquad (9)$$

This expression can be written in terms of natural frequency and damping rate, because

$$\Phi(s) = \frac{1}{\left(\frac{k_e}{\omega_n^2}s^2 + \frac{2\zeta k_e}{\omega_n}s + k_e\right)} = \frac{1}{\left[\frac{k_e}{\omega_n^2}\right][(j\omega_c)^2 + 2\zeta\omega_n(j\omega_c) + \omega_n^2]} \qquad (10)$$

3. Result and Discussion

The results obtained from three case studies are shown below, in which important parameters were varied for the turning process and the bending phenomenon for the machining of alloy steels 1020, 1035 and 1045 under the same working conditions.

3.1. Case study: variation of the damping ratio

Figure 2 shows the behaviour of the stability lobes when the process is exposed to variation in the damping ratio. Values were assigned to this parameter from 0.2 to 0.5 and the value of the natural rigidity and frequency of the system was kept constant. It can be seen that the material that allows the greatest depth of cut in all cases is alloy steel 1020, while alloy steel 1045 is the material that allows the lowest depth of cut. It is also important to note that the depth of cut is proportional to the rate of damping, and as it increases, the stability lobes roll to the right.

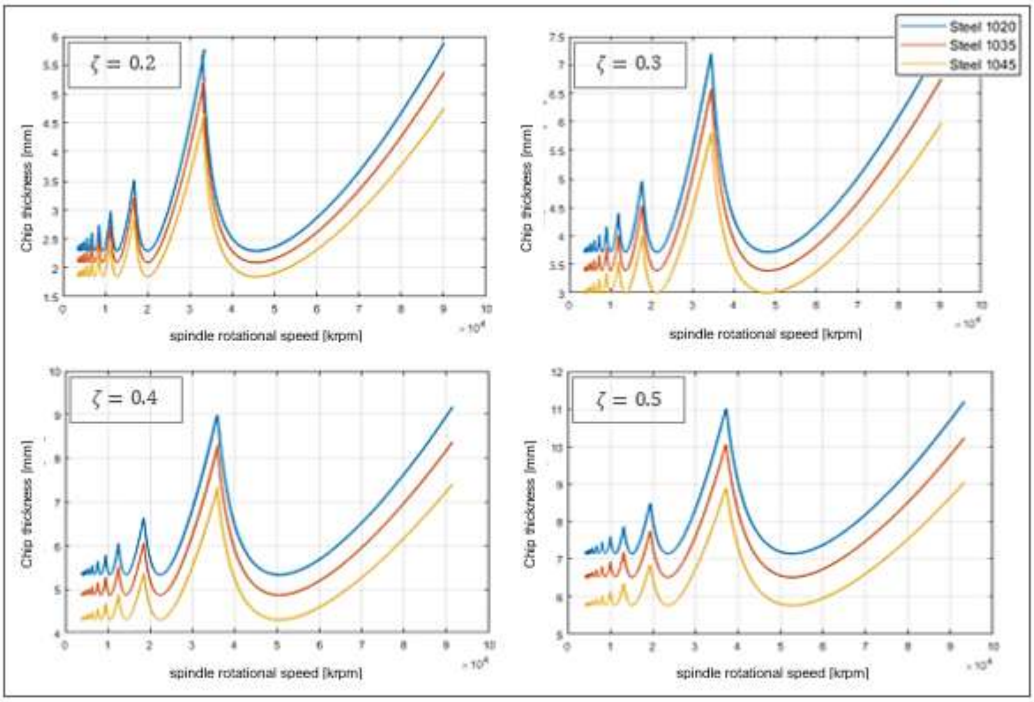

Figure 2.Stability lobes by varying the damping ratio.

3.2. Case study: variation of the natural frequency of the system

The natural frequency of the system is one of the most important factors for the analysis of the re-twisting phenomenon in the machining processes, a way to determine the influence of this on the turning process was to set the damping and stiffness constants at 0.35 and 10 kN/mm respectively, and the natural frequency of the system was varied from 400 Hz to 600 Hz. The Figure 3 shows the performance of the obtained stability lobes, it can be seen that again, alloy steel 1020 is the material that allows greater cutting depth and alloy steel 1045 is the one that presents stability with a lower chip thickness, that is, that this characteristic is inversely proportional to the constant of specific cutting force, characteristic of the material of the workpiece. The change in the natural frequency of the system results in the displacement of the stability lobes to the right, i.e. the stability peaks do not change their magnitude, but the rotation speed at which they are reached.

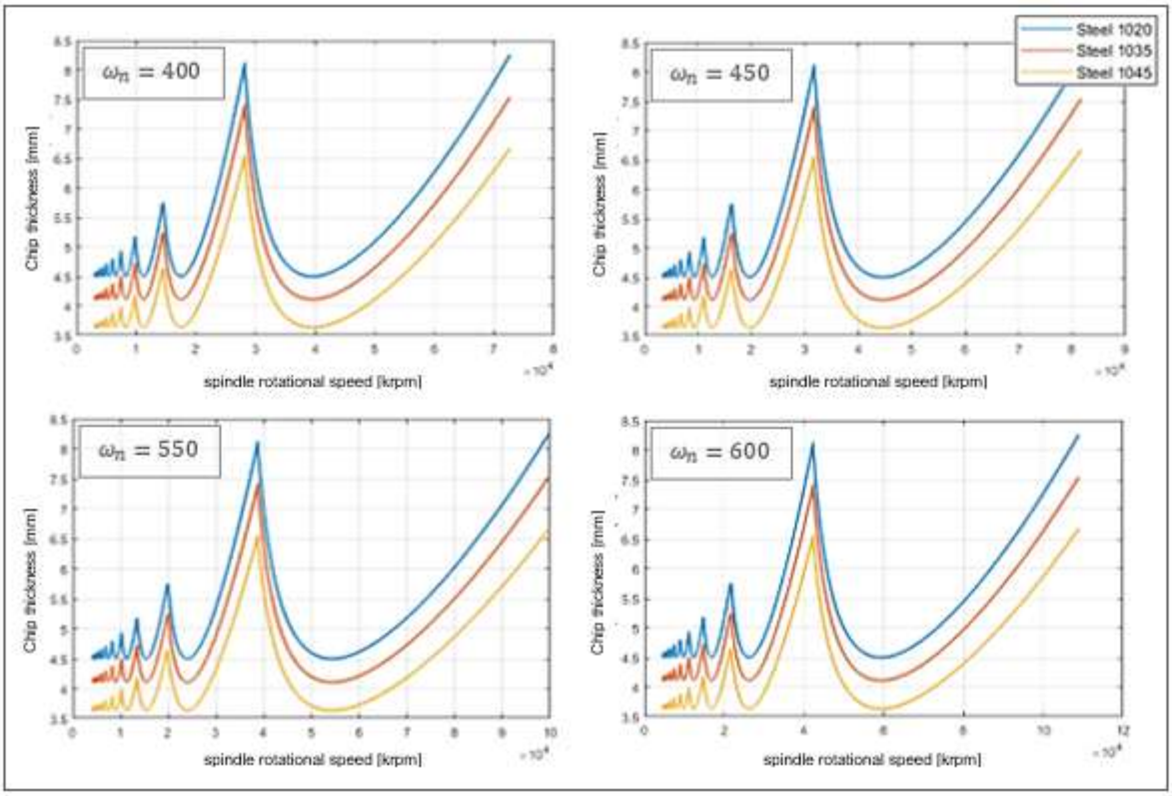

Figure 3.Stability lobes varying the natural frequency of the system.

3.3. Case study: variation of the stiffness ratio

One way to predict the behavior of a machine tool in a turning process is by comparing the various factors that make up the system, in this case the stiffness constant is varied from a value of 8 kN/mm to 12 kN/mm, leaving the natural frequency and damping constant fixed at 500 Hz and 0.35. In the Figure 4. Can be seen that as the stiffness increases, greater penetration of the cutting tool can be achieved, always at the same rotational speed, i.e. these two parameters are directly proportional. The material that allows for the greatest chip thickness once again is 1020 alloy steel, reaching its maximum peak between speeds of 3000 to 4000 rpm.

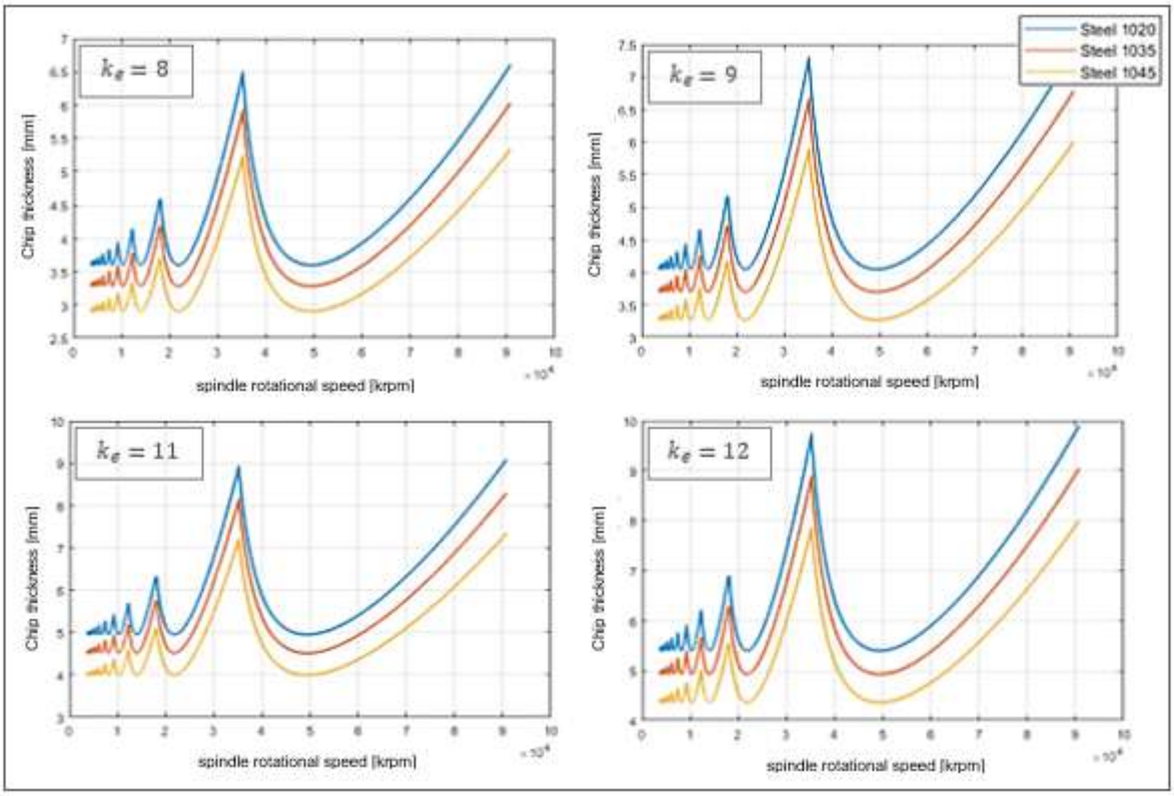

Figure 4.Stability lobes varying rigidity.

4. Conclusions

With the generation of the stability lobe diagrams in the turning process it can be stated that the rotational speed of the spindle and the material removal rate have a directly proportional relationship, helping to the formation of stable machining areas of larger size at high rpm and this leads to selection of higher cutting depths giving greater efficiency in machining. Otherwise, when considering low speed operations (≤ 2000 rpm), the stability lobes have what is known as the asymptotic stability limit, causing the greatest depth of cut that can be reached to become the constant value.

Achieving a dynamically stable cutting operation represents a significant decrease in the production time and therefore in the costs associated with the production process. In the cases of studies carried out in this research, a tendency was observed to increase the stability limit as the damping ratio increased and the lobes shifted slightly to the right, and it was also determined that the material that allowed the greatest depth of cut was 1020 alloy steel. Similar performance was obtained when the stiffness value of the machine tool increased, and the cutting depth was dynamically stable. On the other hand, when the natural frequency of the system increased the stability lobes shifted to the right, however, the magnitude of the stability zones did not change their value.

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