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Stability Lobe Prediction in the Milling of Aluminium 7075 and Aluminium 6061

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Abstract : Machining instability caused by chatter on machine tools is a defect that is to be reduced to avoid the presence of high roughness on the surface of the machined part and rapid and excessive wear of the tool in metal cutting processes. Therefore, this work characterizes the behavior of the milling operations in Aluminum 7075 and Aluminum 6061, through the development of analytical methods for the subsequent generation of stability lobe diagrams, since these allow us to appreciate the working conditions in which the process presents a stable behavior since by means of the analysis of regenerative chatter in the machine tools we can predict the optimal operating point.
In order to arrive at an analysis of the stabilization of the self-excited vibrations in the orthogonal cutting process, the methods proposed by Altinas and Budak are studied, who develop a complete methodology of the subject.
Keywords : Machining, chatter, lobe diagramming, milling.

1. Introduction

A successful machining operation is defined by the dynamic relationship between the cutting tool and the workpiece, on which the quality of the final work depends[1]. The phenomenon of regenerative chatter is defined as the self-excited vibrations of great amplitude that occur in the movement of the cutting tool against the workpiece, under specific circumstances of penetration[2]. The main disadvantages that occur under the influence of the regenerative chatter phenomenon range from affecting the life of the cutting tool to deteriorating the quality of the process, so the development of tools that provide information to control vibration will be important in improving operation and reducing costs[3].

Analysis of the behavior of orthogonal cutting with respect to chatter is of great importance in the quest to improve cutting operations. Budak et al. present the dominant vibration frequency produced when chatter develops, and demonstrate that it is close to the natural frequency of the structure during operation[4]. Gurney

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and Tobias use dynamic systems theory, starting from the harmonic solutions of the characteristic equation, to construct stability lobe diagrams by generating particular graphs[5].

The research carried out on the prediction of the quality of the machined surface shows that the studies remain in stable operating conditions and that the machine tool under vibration is not analyzed, which ultimately affects the quality of the product[6]. Z. Zhao et al. propose a novel method to mitigate the chatter in the operation, by immersion of the working system in viscous liquid, verifying the performance by means of stability lobe diagrams, taking into account different working modes of the thin-walled part[7].

In this work we propose the implementation of a tool capable of generating stability lobe diagrams, with the purpose of studying the influence of cutting parameters on the dynamic stability in the machining operation, developed by José Arenas and Andrés Andión[8], based on the analytical models of Altintas and Budak[4].

2. Methodology

2.1 Analytical prediction of regenerative chatter in the milling process

Due to the directions of rotary force, chip thickness and intermittent cutting periods, the application of regenerative chatter theory is complicated in the orthogonal cutting of machining operations, specifically in milling[9]. For predictive purposes, the cutting tool (cutter) is considered to have two orthogonal degrees of freedom, as shown in **Error! Reference source not found.**[10]. The cutter is assumed to have an N number of teeth with a propeller angle of zero.

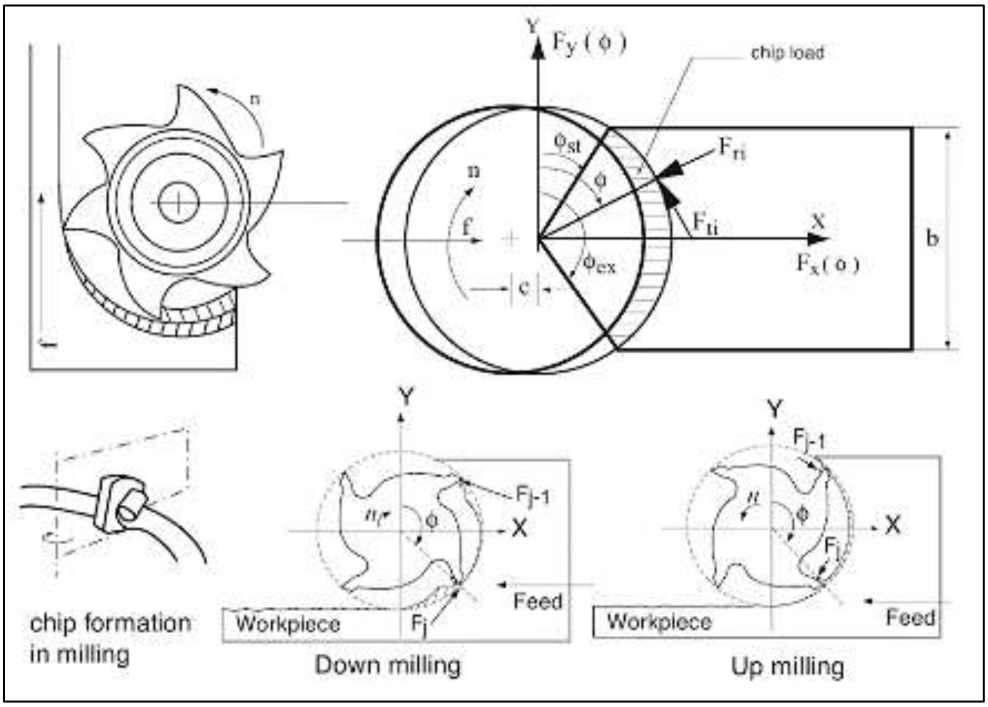

Figure 1: Machine tool milling model with two degrees freedom.

The lobe diagrams are the most precise tools for the verification of the chatter under certain parameters in the machine tool, in this work was used an innovative computer tool designed and developed in the Matlab® software in order to perform analysis and solve real problems related to the milling process, more specifically to solve the problem of regenerative chatter[8]. For the generation of stability lobes, the input parameters of the machine tool must be taken into account, such as the damping constant(ζ), the stiffness constant (ke), the input and output angle of the cutting tool, the natural frequency of the system (ω_n) and the number of teeth the tool has, there are other input parameters concerning the workpiece such as the specific tangential force (kt) and the specific radial force constant(kr).

2.2 Fundamental equations

Considering that the cutting tool in this case has two orthogonal degrees of freedom during the machining process, it is assumed that the tool has an N number of teeth with a helix angle equal to zero for mathematical purposes.

The shear force excites the structure in the direction of feed (X) and normal (Y), causing a dynamic displacement in x and y. Dynamic displacements are carried out on the rotating tooth j in the radial direction or the chip thickness in the coordinates:

$$v_j = -xsin\phi_j - ycos\phi_j \tag{1}$$

Where ϕ_j is the instantaneous angular immersion of tooth j measured clockwise from the normal (Y) axis.

Because the chip thickness is measured in the radial direction (v_j), it can express how:

$$h(\emptyset_j) = \left[s_t \sin\phi_j + \left(v_{j,0} - v_j\right)\right] g(\phi_j) \tag{2}$$

Where $st \sin \emptyset_j$ is the rate of advance per tooth and $\left(v_{j,0}, v_j\right)$ are the dynamic displacement of the tool in the periods of the present and previous teeth, respectively.

The function $g(\phi_j)$ is a single-pass function that determines whether the tooth is in or out of cut:

$$g\left(\emptyset_j\right) = 1 \leftarrow \emptyset_{st} < \emptyset_j < \emptyset_{ex} \tag{3}$$

$$g\left(\emptyset_j\right) = 0 \leftarrow \emptyset_j < \emptyset_{st} \text{ o } \emptyset_j > \emptyset_{ex} \tag{4}$$

Where $\emptyset_{st}$ and $\emptyset_{ex}$ are the angle of entry and exit of the tool.

The static component of the chip thickness $\left(st \sin\phi_j\right)$ is taken from the expressions because it does not contribute to the mechanism of dynamic regeneration of the charge in the chip [10]. Substituting v_j in the equation (2) gives:

$$h(\emptyset_j) = \left[\Delta x \sin\phi_j + \Delta y \cos\phi_j\right] g(\phi_j) \tag{5}$$

Where $\Delta x = x - x_0$ and$\Delta y = y - y_0$. There, (x, y) and (x_0, y_0) represent the dynamic displacement of the tool structure in the periods of the present and previous teeth.

The tangential cutting forces (F_{tj}) and radial cutting forces (F_{rj}) acting on tooth j are proportional to the axial cutting depth (a) and the chip thickness(h):

$$F_{\mathrm{t}j} = K_t a h(\phi_j) \tag{6}$$

$$F_{\mathrm{r}j} = K_r F_{\mathrm{tj}} \tag{7}$$

Resolving the cutting forces in the x and y directions is what you have:

$$F_{xj} = -F_{\mathrm{t}j} \cos\phi_j - F_{\mathrm{r}j} \sin\phi_j \tag{8}$$

$$F_{yj} = +F_{\mathrm{t}j} \operatorname{sen}\phi_j - F_{\mathrm{r}j} \cos\phi_j \tag{9}$$

The sum of the cutting forces presented by all the teeth is written as the total dynamic milling forces acting on the tool as:

$$F_x = \sum_{j=0}^{N-1} F_{xj}\,(\phi_j) \tag{10}$$

$$F_y = \sum_{j=0}^{N-1} F_{yj}\,(\phi_j) \tag{11}$$

Where: $\phi_j = \phi + j\phi_p$, defined as the instantaneous angular immersion of tooth j measured clockwise from the normal (Y) axis. ϕ It's the instantaneous angle of immersion and $\phi_p = 2\pi / N$ it's the angle of passage of the cut.

By substituting the chip thickness presented in the equation (5) and the forces on the tooth given in the equations (6) and (7) in the equations (8) and (9) respectively and, by rearranging the resulting expressions in matrix form, you have:

$$\begin{Bmatrix} F_x \\ F_y \end{Bmatrix} = \frac{1}{2} a K_t \begin{bmatrix} \alpha_{xx} & \alpha_{xy} \\ \alpha_{yx} & \alpha_{yy} \end{bmatrix} \begin{Bmatrix} \Delta x \\ \Delta y \end{Bmatrix} \tag{12}$$

Where the dynamic directional coefficients of the varying forces over time are given in the direction xx:

$$\alpha_{xx} = \sum_{j=0}^{N-1} -g_j\left[\sin 2\phi_j + K_r(1 - \cos 2\phi_j)\right] \tag{13}$$

In the direction xy:

$$\alpha_{xy} = \sum_{j=0}^{N-1} -g_j\left[(1 + \cos 2\phi_j) + K_r \sin 2\phi_j\right] \tag{14}$$

In the direction yx:

$$\alpha_{yx} = \sum_{j=0}^{N-1} g_j\left[(1 - \cos 2\phi_j) - K_r \sin 2\phi_j\right] \tag{15}$$

In the direction yy:

$$\alpha_{yy} = \sum_{j=0}^{N-1} g_j\left[\sin 2\phi_j - K_r(1 + \cos 2\phi_j)\right] \tag{16}$$

3. Results and Discussion

En este artículo se caracteriza el comportamiento de la máquina herramienta en el proceso de fresado, teniendo en cuenta parámetros de entada tanto de la herramienta de corte como de la maquina en cuestión, se comprueba el desarrollo del proceso mediante diagramas de lóbulos comparando las rpm desarrolladas contra la profundidad del corte.

3.1 Case study: variation of the damping constant for milling in Aluminium 6061 and Aluminium 7075

Figure 2 shows the penetration behavior of the cutting tool for these materials at a given rpm, taking into account that the parameters of the machine tool such as the natural frequency and the stiffness constant remain unchanged ($w_n = 675\ y k_e = 6x10^6$), for the purposes of this study, the damping constant of the $\zeta_{x,y} = 0.03$ to $\zeta_{x,y} = 0.05$, in the milling of a 6061 aluminium and a 7075 aluminium. It is important to note that at 1000 rpm both aluminum and aluminum reach their highest cutting depth, however, 6061 aluminum achieves a much higher material removal rate than 7075 aluminum. Another aspect to take into account is the behavior of the system as it increases the damping constant, thus achieving the highest chip thickness.

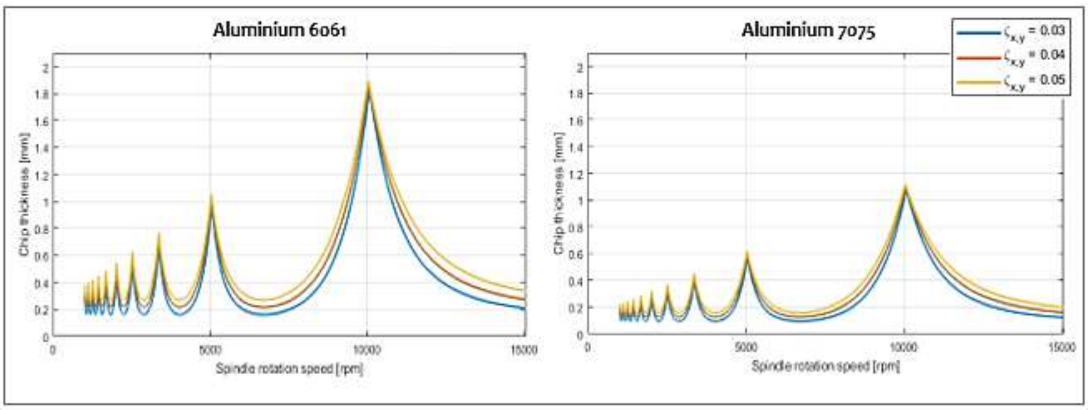

Figure 2: Variation of the damping constant.

3.2 Case study: variation of the natural frequency of the system for milling in Aluminium 6061 and Aluminium 7075

One of the parameters typical of machine tools that have the greatest impact on the analysis of the chatter phenomenon is the natural frequency of the system, therefore, in this case study the damping constant and the stiffness constant are maintained unchanged.$(\zeta = 0.04\ y k_e = 6x10^6)$and the natural frequency of the $w_{n,x,y} = 650$ to $w_{n,x,y} = 700$, as shown in Figure 3. Here it can be seen that as the w_n of the system increases it is necessary to increase the spindle rpm to reach the maximum cutting depth. With respect to the material under study, 6061 aluminium continues to have a greater cutting depth at a specific rpm than 7075 aluminium.

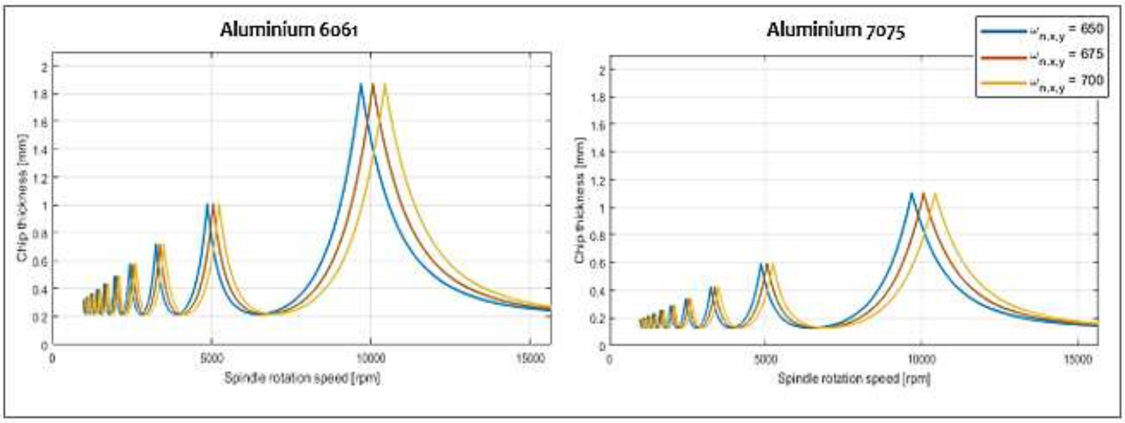

Figure 3. Variation of the natural frequency of the system

3.3 Case study: variation of the stiffness constant for milling in Aluminium 6061 and Aluminium 7075

In case study number 3, the aim is to analyze how the milling process behaves when the stiffness constant is varied $k_{e,x,y} = 5.5 \times 10^6$ to $k_{e,x,y} = 6.5 \times 10^6$and keeping unchanged the other facets such as the natural frequency of the system and the damping constant $w_n = 675$ and $\zeta = 0.03$. Figure 4 shows that the thickness of the chip increases as the stiffness constant increases, although at a small value, reaching the maximum cutting depth in the order of 1000 rpm for both materials.

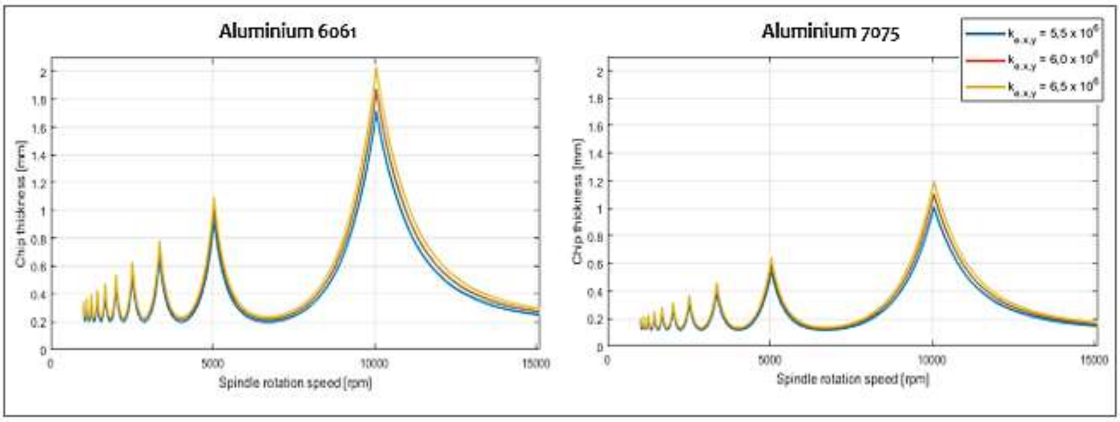

Figure 4. Variation of the stiffness constant.

4. Conclusions

The information provided by the stability lobe diagrams is of great importance for the development of machine tools in matters of stability of the cutting process in the milling operation. These diagrams allow us to know the ranges of spindle rotation speeds and chip thicknesses at which the cutting operation will be dynamically stable and free from the phenomenon of regenerative chatter, which negatively affects the productivity of the operation, resulting in rapid wear of the cutting tool and low quality surface finishes, which represents a significant increase in production time and therefore in the costs associated with the production process.

After characterizing and analyzing the stability lobe diagrams for milling processes, it can be stated that the rotational speed of the spindle is directly proportional to the material removal rate. It should be noted that at high rpm there are larger stable zones (pockets) in the diagrams where higher cutting depths can be selected, on the other hand, at low rpm($\leq 2000\ rpm$), the stability lobes get very close together, causing the greatest depth of cut that can be reached to become a constant value, which would be the minimum point of the lobes known in the literature as the asymptotic stability limit.

It is important to emphasize that the reliability of the application results is closely related to the accuracy of the value of the characteristic constants of the vibratory system such as the natural frequencies (w_n), the damping constants (ke) and the rigidity constants (ζ) of the tool coupling system in the tangential and radial directions, calculated by modal testing techniques, and the specific cutting force that depends on the material of the part to be machined and the operating conditions such as feed rate and speed. The specific shear force for commercial metals is calculated by experimental testing by their manufacturers and is available to the public.

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