Study and Analysis of the Chatter in the Milling the Stainless Steel 302 and Alloy Steel 4140

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Abstract

The instability in machining 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 part and the rapid wear of the tool in metal cutting processes. For this reason, this work characterizes the behavior of the milling operations in stainless steel 302 and alloy steel 4140, 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. The aim of this article is to compare the milling operation performance of these materials taking into account specific cutting parameters, which are specific to machine tools.

Keywords: machining, chatter, lobe diagram, milling

1. Introduction

The dynamic relationship between the cutting tool and the workpiece is what defines a successful machining operation [1]. Chatter is defined as self-excited vibrations of great amplitude that occur in the movement of the tool against the workpiece, under specific circumstances of penetration [2]. The disadvantages of chatter range from affecting tool life to deteriorating cutting quality, so generating...
a tool that provides information to control this phenomenon will result in operational improvements and cost reduction [3].

Analysis of the behaviour of orthogonal cutting with respect to chatter is of great importance in the quest to improve cutting operations. Gurney and Tobias use the theory of dynamic systems, starting from the harmonic solutions of the characteristic equation, to construct stability lobe diagrams by generating particular graphs [4]. Budak et al. present the dominant vibration frequency produced when the chatter develops, and demonstrate that it is close to the natural frequency of the structure during operation [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 [6]. Z. Zhao et al. propose a novel method to mitigate chatter in operation by immersion of the working system in viscous liquid, verifying performance by means of stability lobe diagrams, taking into account various working modes of the thin-walled part [7].

This work proposes the implementation of a tool capable of generating stability lobe diagrams, with the purpose of studying the influence of cutting parameters on dynamic stability in the machining operation, developed by José Arenas and Andrés Andión [8], based on the analytical models of Altintas and Budak [5].

2. Methodology

2.1. Analytical prediction of regenerative chatter in the milling process

In orthogonal cutting of milling operations, the application of chatter theory is complicated by the directions of rotary force, chip thickness and intermittent cutting periods [9]. For predictive purposes, the cutting tool (cutter) is considered to have two orthogonal degrees of freedom, as shown in Figure 1. The cutter is assumed to have an N number of teeth with a propeller angle of zero.

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 (wn) 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).
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2.2. Fundamental Equations

The cutting tool (cutter) can be considered to have two orthogonal degrees of freedom. The tool is assumed to have an N number of teeth with a propeller angle of zero.

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:

\[ v_j = -x \sin \phi_j - y \cos \phi_j \] (1)

Where \( \phi_j \) 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:

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

Where \( st \sin \phi_j \) is the rate of advance per tooth and \( (v_{j,0}, v_j) \) 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:
\[ g(\varnothing_j) = 1 \iff \varnothing_{st} < \varnothing_j < \varnothing_{ex} \] (3)

\[ g(\varnothing_j) = 0 \iff \varnothing_j < \varnothing_{st} \lor \varnothing_j > \varnothing_{ex} \] (4)

Where \( \varnothing_{st} \) and \( \varnothing_{ex} \) are the angle of entry and exit of the tool.

The static component of the chip thickness \((st \sin \phi_j)\) 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 equation (2) gives:

\[ h(\varnothing_j) = [\Delta x \sin \phi_j + \Delta y \cos \phi_j]g(\phi_j) \] (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 \((h)\):

\[ F_{tj} = K_t a h(\phi_j) \] (6)

\[ F_{rj} = K_r F_{tj} \] (7)

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

\[ F_{xj} = -F_{tj} \cos \phi_j - F_{rj} \sin \phi_j \] (8)

\[ F_{yj} = +F_{tj} \sin \phi_j - F_{rj} \cos \phi_j \] (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:

\[ F_x = \sum_{j=0}^{N-1} F_{xj}(\phi_j) \] (10)

\[ F_y = \sum_{j=0}^{N-1} F_{yj}(\phi_j) \] (11)

3. Results and discussion

In this article the behavior of the machine tool in the milling process is characterized, taking into account the input parameters of both the cutting tool and the machine in question, the development of the process is checked by means of lobe diagrams comparing the \( rpm \) developed against the depth of the cut.
3.1. Case study: variation of the damping constant for milling in Stainless Steel 302 and Alloy Steel 4140

The Figure 2 shows the penetration of the cutting tool with the spindle rotation speed, taking into account that the parameters of the machine tool such as the natural frequency and the stiffness constant are maintained without variation ($w_n = 675 \times k_e = 6 \times 10^6$), in this case the damping constant of $\zeta_{x,y} = 0.03$ is varied to $\zeta_{x,y} = 0.05$, in the milling process of stainless steel 302 and alloy steel 4140. It is important to highlight the similarity in the behavior of these two materials, taking into account that at a speed of rotation of the spindle specifies that stainless steel 302 reaches a thickness of chip a little greater than the alloy steel 4140. It can also be observed that when the machine tool has a $\zeta_{x,y} = 0.05$ the process reaches better cutting depths with the same speed of the spindle compared to the other configurations.

![Figure 2. Variation of the damping constant ($\zeta$).](image)

3.2. Case study: natural frequency variation of the milling system for Stainless Steel 302 and Alloy Steel 4140

The natural frequency of the system is one of the most important factors in the analysis of the phenomenon of chatter in machine tools, a way to observe how much this parameter influences the machining process is to maintain the damping constant and the stiffness constant without variation ($\zeta = 0.04 \times k_e = 6 \times 10^6$) and modify the natural frequency of the system from $w_{n,x,y} = 650$ to $w_{n,x,y} = 700$, as shown in Figure 3. Here you can see how as the $w_n$ of the system increases it is necessary to increase the rpm of the spindle to reach the maximum cutting depth. In this case, stainless steel 302 continues to achieve higher chip thicknesses than alloy steel 4140 in these operating parameters.
3.3. Case study: variation of the stiffness constant for milling in Stainless Steel 302 and Alloy Steel 4140

In this case, the aim is to analyze the behavior of the milling process when the stiffness constant varies from $k_{e,x,y} = 5.5 \times 10^6$ to $k_{e,x,y} = 6.5 \times 10^6$ taking into account that the other factors such as the natural frequency of the system and the damping constant are not modified, $w_n = 675$ and $z = 0.03$. Figure 4 shows the small increase in chip thickness (mm) as the stiffness constant increases, reaching the maximum cutting depth in the order of 1000 rpm. Despite its similar behaviour, it can be seen that 302 stainless steel continues to achieve higher chip thicknesses than 4140 alloy steel under these specific cutting parameters.

4. Conclusions

The stability lobe diagrams provide valuable information about the stability of the cutting process in milling operations. They 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, producing a rapid wear of the cutting tool and generating low quality surface finishes which represents a significant increase in production time and therefore in the costs associated with the production process.

After studying the stability lobe diagrams for milling processes, it can be stated that as the rotational speed of the spindle increases, the material removal rate also increases significantly because 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 (≤ 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 note 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, the damping constants and the rigidity constants 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.

References


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