Increasing Productivity in High Speed Milling of Airframe Components Using Chatter Stability Diagrams

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Abstract: In this study, the application of chatter stability diagrams in industrial operations is presented with representative cases. Challenges arising due to the practical aspects of production systems are discussed in detail. Effects of tool, tool holder, spindle and CNC machine on chatter stability diagrams are presented. The implementation of the stability diagrams under such challenges is presented through real application examples showing significant reduction in machining times.
Keywords: High speed milling, airframe component machining, chatter stability diagrams

1. INTRODUCTION

Chatter is one of the most important problems in machining causing high cutting forces, drastically reduced tool lives, and undesired surface qualities yielding increased machining costs. In general, intuitive solutions cannot suppress chatter, instead scientific based approaches should be considered.

The mechanics of instability in cutting processes was first understood by Tlusty [Tlusty et al., 1963] and Tobias [Tobias et al., 1958]. It was observed that the modulated chip thickness due to vibrations affects cutting forces dynamically, which in return increases vibration amplitudes yielding a process named as the regenerative chatter. They also observed that the depth of cut was the key process parameter in the cutting process stability. Tlusty [1963] analytically showed that for the depth of cuts higher than the stability limit, the magnitude of the dynamic forces and oscillations increases yielding instability, thus chatter vibrations.

Although chatter is a common problem for all machining operations, it is particularly critical for milling applications. First of all, chatter is very common in milling due to the low dynamic rigidity existing in many cases. On the machine tool side, spindle-holder-tool assembly generally represents a flexible structure due to many interfaces and slender tools. On the other hand, flexible parts such as thin walled structures also reduce the dynamic rigidity of the milling system. The stability analysis of milling is complicated due to the rotating tool, multiple cutting teeth, periodical cutting forces and chip load directions, and multi-degree-of-freedom structural dynamics, and has been investigated using experimental, numerical and analytical methods. In the early milling stability analysis, Tlusty [2000] used his orthogonal cutting model considering an average direction for the cut. Later, however, Tlusty et al. [1981] showed that the time domain simulations would be required for accurate stability predictions in milling. Minis et al. [1990, 1993] used Floquet's theorem and the Fourier series for the formulation of the milling stability, and numerically solved it using the Nyquist criterion. In a later study Budak and Altintas [Altintas et al., 1995, Budak et al., 1998] developed a stability method which leads to analytical determination of stability limits. The method was verified by experimental and numerical results, and demonstrated to be very fast for the generation of stability lobe diagrams.

The studies presented above are only applicable to 3 axis end milling operations. In later studies the chatter models for ball-end mill tools [Shamoto et al., 2009, Altintas, 1998], and 5 axis milling operations [Ozturk et al, 2007, 2008, Budak et al, 2009] were also developed.

In practice, stability diagrams can be used in selection of cutting depths and speeds in order to suppress chatter. However, implementation of these diagrams in production presents some challenges. This is mainly due to the nature of aerospace production operations where many different parts are manufactured at small quantities. In order to increase flexibility, a part can be machined on different machines where same part programs are desired to be used. In those cases, stable conditions common to all combinations of tools, tool holders and machines need to be identified. In this study, implementation of the stability diagrams in airframe part production is presented. Increased productivity through chatter suppression is demonstrated with several example applications. It is shown that significant improvements in milling cycle times can be achieved through stable cutting conditions obtained from stability diagrams.

2. CHATTER STABILITY DIAGRAMS

In this section, milling process dynamics and stability are summarized. The details of the formulation can be found in [Altintas et al., 1995, Budak et al., 1998]. The milling cutter and workpiece are considered to have two orthogonal modal directions as shown in Figure 1. Milling forces excite both cutter and workpiece causing vibrations which are imprinted on the cutting surface. Each vibrating cutting tooth removes the wavy surface left from the previous tooth resulting in modulated chip thickness which can be expressed as follows:

$$h_j(\phi) = [\Delta x \sin\phi_j + \Delta y \cos\phi_j] \quad (1)$$

where ϕ_j is the angular immersion of tooth (j) and Δx and Δy are the dynamic displacements at the given directions.

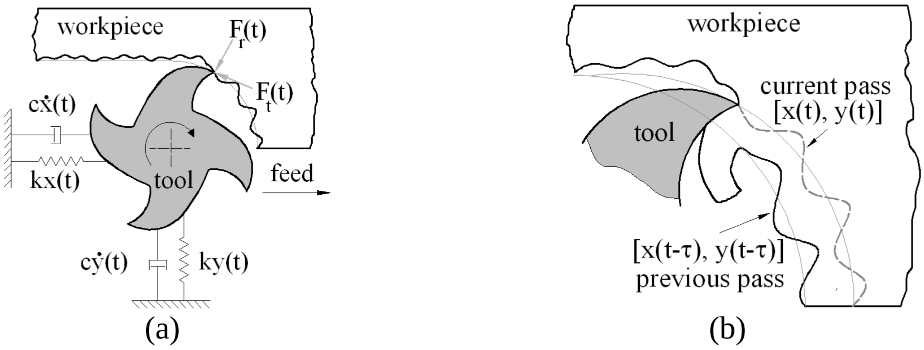

Figure 1: (a) Cross sectional view of an end mill showing regeneration and dynamic forces, and (b) a closer look to the dynamic chip thickness.

The static part of the chip thickness is neglected in the stability analysis. The dynamic displacements are defined as follows:

$$\begin{aligned} \Delta x &= (x_c - x_c^o) - (x_w - x_w^o) \\ \Delta y &= (y_c - y_c^o) - (y_w - y_w^o) \end{aligned} \tag{2}$$

where (x_c, y_c) and (x_w, y_w) are the dynamic displacements of the cutter and the workpiece in the x and y directions, respectively. The superscript (o) denotes the dynamic responses in the previous tooth period which are imprinted on the cut surface. The dynamic cutting forces on tooth (j) can be solved in order to obtain the relation between the chatter frequency and the spindle speed [Budak et al., 1998]:

$$\omega_c T = \varepsilon + 2k\pi \qquad \varepsilon = \pi - 2\tan^{-1}\kappa \qquad n = \frac{60}{NT} \tag{3}$$

where ε is the phase difference between the inner and outer modulations, k is an integer corresponding to the number of vibration waves within a tooth period, n is the spindle speed (rpm), N is the number of teeth, ω_c is the chatter frequency, and κ is the term which includes the Frequency Response Function (FRF) of the system. Finally, the stability limit is obtained as follows [Budak et al., 1998]:

$$a_{\lim} = -\frac{2\pi\Lambda_R}{NK_t}\left(1+\kappa^2\right) \tag{4}$$

where K_t is the cutting force coefficient at the tangential direction. Therefore, for given cutting geometry, cutting force coefficients, tool and workpiece FRF's, and chatter frequency ω_c, the corresponding spindle speed and the stability limit can be calculated using equations (3) and (4). When this procedure is repeated for a range of chatter frequencies and number of vibration waves k, stability lobe diagram for a milling system is obtained. Among the other inputs there are two important parameters when developing the stability diagram: cutting force coefficients and FRF of the cutting system.

The cutting force coefficients can be directly obtained from calibration tests, or by using the mechanics of milling approach proposed by Armarego et al. [1985] and Budak et al. [1996]. FRF of the system is generally measured using modal analysis techniques.

3. PRACTICAL ASPECTS OF IMPLEMENTING STABILITY DIAGRAMS

In practice, stability diagrams can be mostly affected by two parameters: material and the FRF of the cutting system. Changes in material characteristics result in variations of stability limits since the stability limit has an inverse relationship with the cutting force coefficient (Eq.4). As for the FRF there are several important parameters. First of all, the FRF of the cutting system is represented at the tip of the milling tool which is affected by the spindle-tool holder-tool assembly dynamics. Hence, parameters such as tool length, clamping type, tool holder material and spindle design have different effects on the tool point dynamics, and thus stability diagrams. In this section, these effects are demonstrated together with practical solutions in production applications. All the examples given in this section are real production applications, and their stability diagrams are calculated for uncoated carbide tools and AL 7050 work material using CutPro®.

3.1. Cutting Tool

The length of the cutting tool generally determines its modal frequencies, and thus the stability pocket positions and the stability limit. If the tool length is increased, the location of the stability pockets move to the left, i.e. slower spindle speeds, and the stability limits become lower. The stability diagrams obtained for three different tool lengths can be seen in Figure 2. Although increasing tool length decreases the stability limit, it may sometimes be favorable in obtaining the stability pockets at lower speeds. Observing Figure 2 it can be seen that there is a stability pocket at 10300 rpm for the tool with 53 mm length and a stability pocket at 9600 rpm for the tool with 78 mm length. Therefore with a CNC machine having maximum 10000 rpm spindle speed, the tool with 78 mm length serves the best for the stability pocket position. However since the stiffness of the tool becomes lower as it length is increased, the deflections during the operations should also be taken into account before deciding for the optimum cutting parameters.

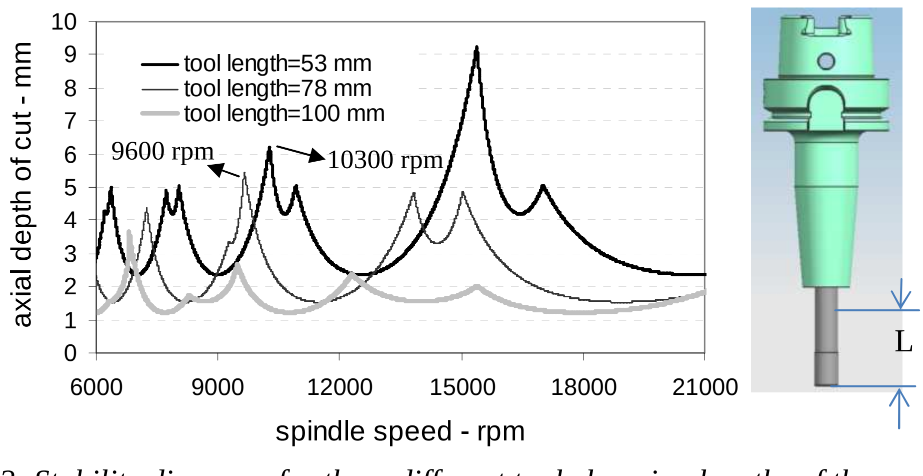

Figure 2: Stability diagrams for three different tool clamping lengths of the same tool having 20 mm diameter in slot milling

Another important issue is the selection of the diameter of the tool. Although the tool diameter is very much related to the dimensions of the features on the workpiece and the maximum torque of the spindle, it may be still optimized in terms of stability. Such an example can be seen in Figure 3. As expected, increase in the diameter increases the stiffness of the tool, resulting in increased stability limits.

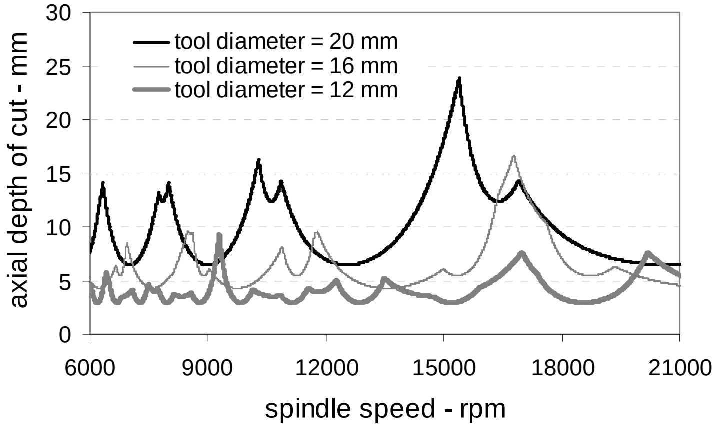

Figure 3: Stability diagrams for three different tool diameters with half-immersion.

3.2. Tool Holder Effects

Tool holder is another important component which affects the dynamics at the cutting tool tip. The example in Figure 4 represents the stability diagrams for shrink fit tool holders having two different holder lengths. Observing Figure 4, it can be seen that the tool holder length do not effect the absolute stability limit in this case. Therefore, it can be concluded that the most flexible component of the system is not the tool holder. However, the dynamics of the tool holder may still affect the stability diagram. For instance, the holder with 105 mm length results in stability lobes which trims some stability pockets around 12500 rpm and 14500 rpm. Therefore, this should be taken into consideration if different holders are used in production for the same tool

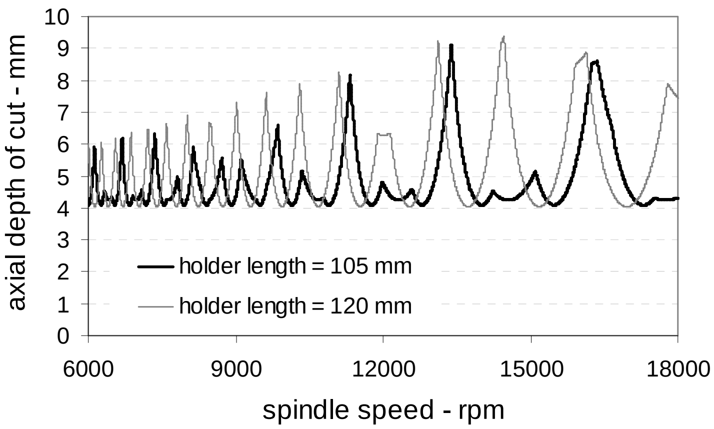

Figure 4: Stability diagrams for two shrink fit holders with different lengths.

In addition, tool holders with same length but different cross sections are compared (Figure 5). As can be observed from Figure 5, the thick tool holder's stability limit is around 6 mm where it is 2 mm for the slim tool holder. Another important parameter in terms of stability is the type of the tool holder. In this study three different tool holder types are considered: shrink fit, hydraulic, and collet chuck. The calculated stability diagrams can be seen in Figure 6. Firstly, comparing the absolute stability limits, shrink fit type tool holder provides the best result which is 1 mm better than the other tool holder types. It is interesting to note that there exists a common favorable pocket for all types around 19000 rpm.

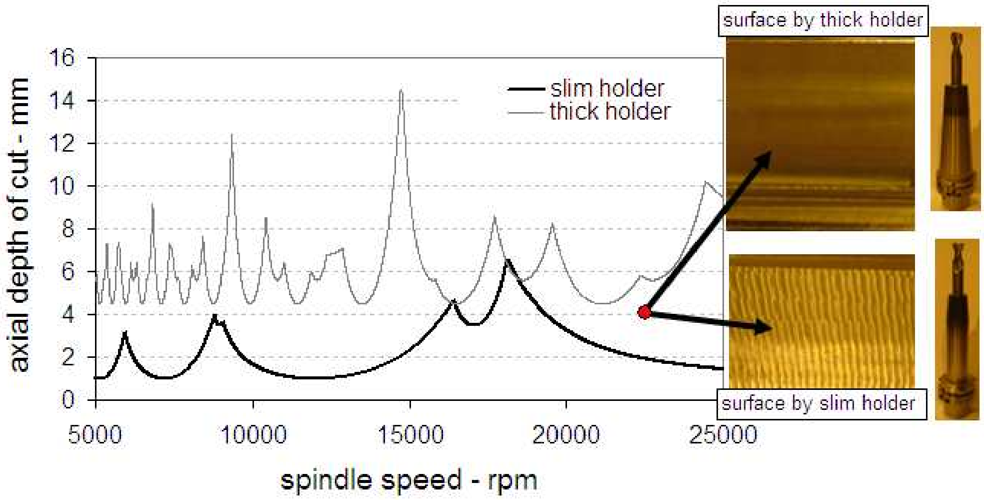

Figure 5: Stability diagrams and experimental surface for two holders having same length but different cross sections.

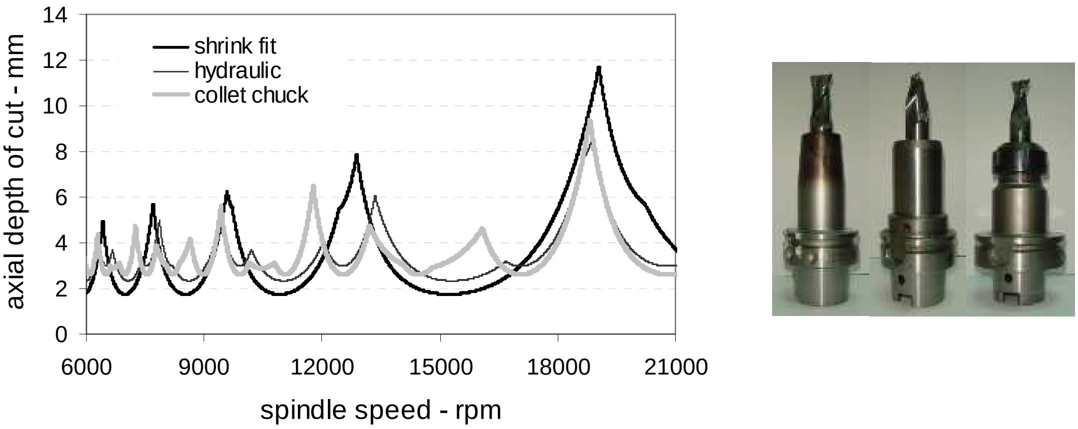

Figure 6: Stability diagrams for three different types of tool holders. Tool diameter and radial depth of cut is 20 mm.

3.3. Spindle Dynamics

Spindle is one of the most problematic components in terms of the application of the stability diagrams in practice. The problem arises from the change in the dynamic characteristics of the spindle over time which is mostly related to the wear of the ball bearings. Therefore, a stability diagram that is developed for the new spindle may change over time. Moreover, when the spindle is changed a new stability diagram should be calculated in order to select the best cutting parameters. In Figure 7 comparisons of two stability diagrams calculated before (old spindle) and after (new spindle) the change of a spindle can be seen. As can be observed from Figure 7 some favorable areas became unstable regions after the change which resulted in higher absolute stability limit and wider stability pockets. Thus, it can be deduced once again that, conditions which are very close to the stability boundaries should not be selected since even slight variations in the dynamics may shift the stable cutting regains.

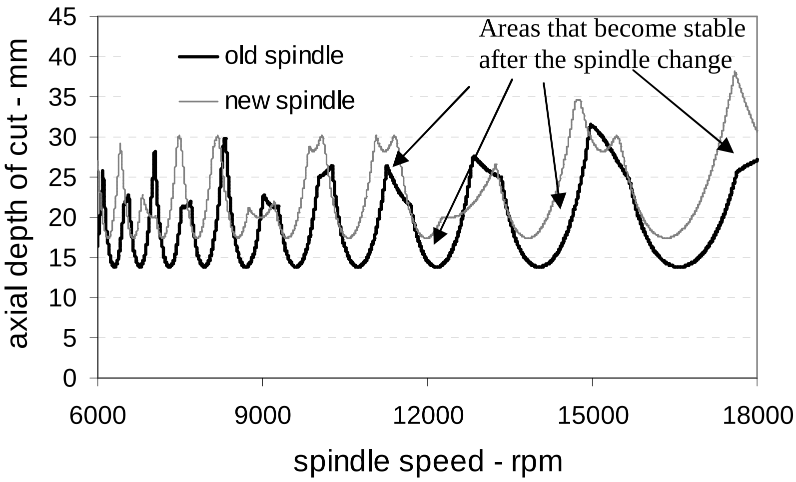

Figure 7: Stability diagrams for old and new spindle.

3.4. Effects of Machine Tool

In many production lines there are multiple similar or exactly the same machine tools to create additional capacity and flexibility. It is a very well known problem that the qualities of the parts manufactured on separate machines of the same brand and model may differ even if the same cutting conditions are used. Therefore, the stability diagrams determined for a specific machine tool may not be valid for the other machines of the same series. On the other hand, one would like to use the same CNC part program on all machines in order to reduce planning time. Such an example can be seen in Figure 8 which shows stability diagrams for four different high speed, 5 axis machining centers of the same brand and model. As can be observed from this figure, even the machine brand and the models are the same there is no common stability pocket. However, a common stability boundary can be obtained which is shown by the bold line in Figure 8 indicating a common favorable pocket around 15000 rpm. Therefore, this common stability diagram can be used to select the best cutting parameters for these 4 machine tools.

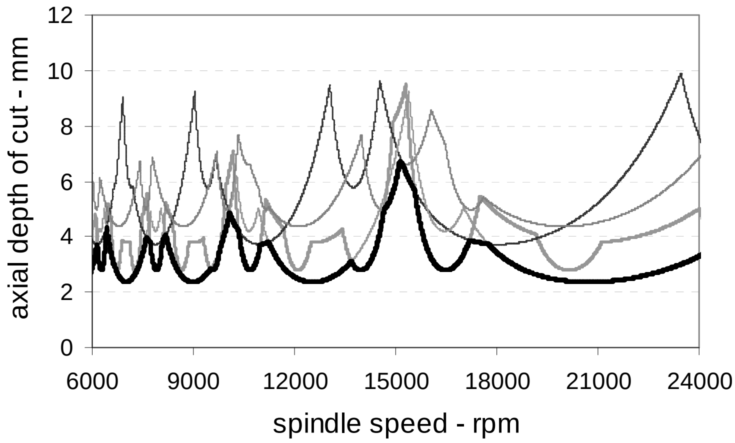

Figure 8: Stability lobes for 4 different machines having the same brand and model. The bold line is the trimmed stability diagram.

4. IMPLEMENTATION OF STABILITY DIAGRAMS IN PRODUCTION

Chatter suppression in high speed milling of airframe components through implementation of stability diagrams has been done in Turkish Aerospace Industries Inc. (TAI). Tap testing and modal analysis techniques have been used in order to measure FRF's of all milling tools that are being used in machining of these components. The combinations of the same tool on different machines, with different tool holder types and clamping lengths have also been taken into consideration. After obtaining the FRFs, TAI uses CutPro® software in order to obtain stability diagrams which determine the stable regions in terms of depth of cut and spindle speed. TAI also conducts cutting mechanics simulations using CutPro® in order to calculate the cutting torque and power needed for a machining operation. Eventually torque limits are embedded in the stability diagrams for a selected feed rate. Such a diagram can be seen in Figure 9. By the help of this diagram, the integration of feed rate effect is also achieved and can be used to determine maximum possible stable material removal rate. In order to build a systematic approach in the company, TAI generated a database of FRF's and stability diagrams of all cutting tools which are used in selection of optimal machining conditions for increased productivity.

The selection of best cutting parameters for aerospace part programs is achieved by using the stability diagrams. An example application is presented here. The part in this example case is made of AL7050 and all the cutting tools are uncoated carbide end mills. The two faces of the part are machined on the same milling CNC machine, one by one with appropriate fixtures. There are four milling tools that are used on the top side, and three milling tools used for the other side. The old and updated parameters and the machining time comparisons can be seen in Table 1. As can be observed from Table 1 the total cycle time is reduced 45%. The part passed all quality inspections.

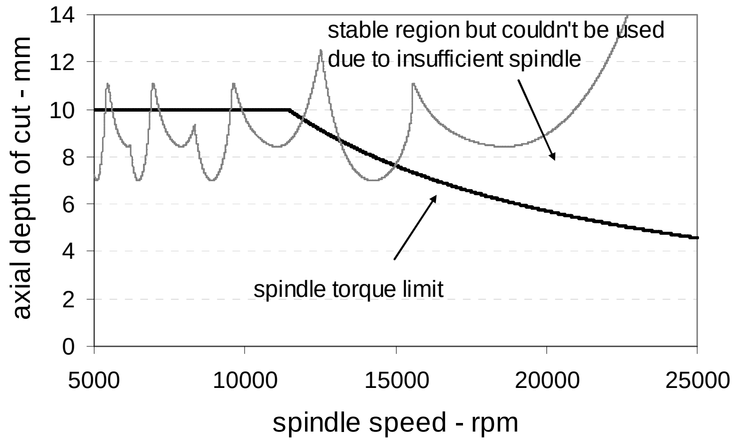

Figure 9: Stability diagram together with the spindle torque limitation.

5. CONCLUSIONS

In this study, challenges that may arise during the application of stability diagrams in practice are discussed. Effects of several parameters such as tool dimensions, tool holder type and length, spindle, and manufacturing environment on the stability diagrams are presented with the real industrial applications. It is shown that these challenges can be overcome by proper analysis and systematical approach yielding significant savings in cycle times. Although several recommendations are presented throughout the paper, as a general conclusion, it is recommended to select favorable regions in the stability pockets which are not very close to the stability boundaries.

Table 1: The old and updated cutting parameters using science based approaches in milling for an example part.

Side	Tool	Axial Depth (mm) OLD/NEW	Spindle Speed (rpm) OLD/NEW	Increase in Performance (%)	OLD Mach. Time (min)	NEW Mach. Time (min)	Diff. (%)
Top	20 mm dia. Short	2.54 / 5	15000 / 18000	70	62.2	35.1	-43.7
	20 mm dia. Long	2.54 / 5	15000 / 16800	68	23.8	10.3	-56.7
	12 mm dia.	1.27 / 3	15000 / 17500	63	16.9	6.5	-61.4
	10 mm dia. 5 mm rad.	1.27 / 2	15000 / 20000	96	46.1	23.3	-49.6
Down	20 mm dia. Short	2.54 / 5	15000 / 18000	70	36.1	19.7	-45.4
	12 mm dia.	1.27 / 3	15000 / 17500	63	26.7	13.8	-48.2
	10 mm dia. 5 mm rad.	1.27 / 2	15000 / 20000	96	48.4	22.6	-53.4
TOTAL					283.8	154.9	-45.4

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