# NEAR DRY MACHINING (NDM) BY DROPPING IN TURNING OF STAINLESS STEELS

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*Abstract. Machining industries are deeply concerned about reducing cutting fluids without any losses on productivity and quality. On the other hand, rigid environmental laws referring to fluid disposal require expensive equipment and high cost processes. Therefore, methods of near dry machining (NDM) are becoming a suitable alternative to reduce costs and eliminate, significantly, high amounts of fluid which would be rejected at the end of its life. In addition, production of clean and dry chips also contributes to get better value for recycling. This work presents a comparison between the conventional fluid application (by gravity and high volume - 150 liters/hr) and the method of NDM (applying cutting fluid by dropping - 90 ml/hr). Both methods were evaluated considering maximum flank wear (VBmax) of cutting tools a performance parameter for different cutting conditions. Results suggest that only in a few conditions of severe heating, conventional method presented slightly better tool life and, for most of the investigated conditions, method of NDM showed good lubrication in tool-workpiece interface and enough cooling, determining an excellent performance of tool life and integrity of cutting edge. Some additional analysis of wear modes, by microscope and comparison of generated chips indicated that, even for low machinability materials, method of NDM is suitable for a large range of cutting conditions.*

***Keywords***: *machining, minimum amount of fluid, stainless steels, turning.*

## 1. Introduction

Operational costs related to production, environmental policies and legal demands to human health are some of the reasons for reducing the use of cutting fluids (Heisel and Lutz, 1998) (Kalhofer, 1997). On the other hand, the use of fluids in machining is still essential in many cases, specially for raising tool lives and surface finishing improvements (Belejchak, 1997), although the importance of reduce or even completely eliminate cutting fluids

The alternatives to minimize amount of fluid are: dry machining (complete elimination of fluid), and near dry machining (NDM) (Sales *et al.*, 2001).

Dry machining has some restrictions:

- generally is applied to finishing operations with special inserts or for roughing uses to lower volumes of removed material (Diniz and Oliveira, 2004);
- with cermet inserts, to avoid thermal shocks and, consequently, thermal cracks, reducing tool life; in addition, this type of insert tends to present better performance in higher temperatures.

Moreover, in general, dry cutting tends to reduce tool life for the high temperatures generated during machining operation. Methods to minimize amount of fluid in cutting processes were made possible just because of the significant developments in tool materials technology (Sandvik, 1996).

It is important to remember that dry cutting is not recommended in processes with poor chip removal as drilling operations where the fluid has the additional function of cleaning the drilled hole.

NDM as the other alternative for reducing the amount of fluid in machining processes (Heisel *et al.*, 1998) and it is characterized by::

- Rates of flow between 10 to 100 ml/hr, according to some authors or from 200 to 300 ml/hr, according to others (Machado and Wallbank, 1997);
- Application method of NDM aims mainly the cutting area, defined by tool-workpiece-chip interface;
- Lubrication action of the fluid is much more significant than cooling effect (Braga *et al.*, 2000).

## 2. Method of Near Dry Machining (NDM)

There are different methods known as NDM (Heisel *et al.*, 1998):

- Dropping method – Consists of small emulsion drops in the tool-chip interface. In this case, the device is quite simple and, in some cases, is the same system used for conventional method adjusted for a very low flow.
- Spray method – The fluid is displaced by a "Venturi" effect, mixing air and liquid which is directly applied to the cutting interface. In this case, the rates of flow are considerably high (from 0.5 to 10 liters/hr).
- Dropping method with pneumatic alternative pumps – Pulsing feed of a specific amount of fluid to machining surface, without air assistance. Flow rates are adjustable according to pump type, varying from 0.1 to 1 ml/cycle.
- Spray method with separate feed piping – Lubricant is mixed to compressed air supplied from a separate device, so the amounts of air and lubricant can be adjusted to optimum performance. In this case, there is a low fluid consumption (from 10 to 100 ml/hr).

Methods of NDM mentioned above are different in flow rates but, in all cases, fluid volumes are significantly lower when compared to conventional method. Follows, one can consider a hypothetic case for justify reduction of fluid volumes for lubricating a machining operation (Machado and Wallbank, 1997):

In a typical turning process, with cutting speed of 200 m/min, depth of cut of 2 mm and feed rate of 0.2 mm/rot, chip surface area per minute is around 400,000 mm$^2$. For an effective lubrication, fluid must reach chip-workpiece interface for obtaining a molecular layer, which would require 400,000x10$^{12}$ atomic chains. Avogadro's theorem stands that 1 mol of a substance (molecular mass in grams) there are 6023x10$^{23}$ molecules; so, in each minute, 400,00x10$^{12}$/6023x10$^{23}$ moles of lubricant are required. For an illustrating example, water has a molecular weight of 18, so required mass flow is 7.2x10$^{-4}$ g/hr (or 7.2 ml/hr). Assuming an efficiency of only 1%, which means that, from all applied lubricant, only 1/100 is effectively used in the process, required flow is around 0.07 ml/hr. Therefore, in a real machining process, there is a significant waste of fluid, when applied by conventional method for reach chip-workpiece interface (Heisel and Lutz, 1998), which justifies the use of methods for flow reduction of cutting fluids.

Table 1 presents a comparison between advantages and disadvantages of NDM method.

Table 1. NDM method characteristics (Machado and Wallbank, 1997) (Sales *et al.*, 2001).

| Advantages | Disadvantages |
|---|---|
| - Low lubricant consumption.<br>- Disposal problems are eliminated.<br>- Circulation system is not necessary.<br>- Reduction of operations of parts washing.<br>- Clean chips, meaning better recycling value.<br>- Reduction of health problems with machine operators.<br>- No need of biocides in fluid reservoir.<br>- Better use of generated heat in the process with reduction of cutting forces. | - More mist and oil smokes in air.<br>- Elevated tooling costs, in some cases, because of tool wear.<br>- Less protection of machine parts against corrosion once there is no fluid excess.<br>- Difficult chip disposability.<br>-Difficult fluid penetration when there is chip accumulated on the rake face.<br>- Less heat dissipation.<br>- Its use is restricted to lower cutting speeds and when lubrication is more important than cooling. |

Performance of cutting process can be evaluated by parameters like tool wear rates, surface finish, cutting forces and temperature (Heisel *et al.*, 1998).

## 3. Stainless steels machining

The importance of research on stainless steels machining is related to the fact that 50% of all manufactured products of this material are submitted to some kind of significant cutting operation before reaching its final shape (Capuccio *et al.*, 1996). The reason for this is because of the great search for materials that require less time for maintenance and are more suitable for environment (Chandrasekaran *et al.*, 1994) . Because of their composition, these materials – specially the austenitic type – are easily hardened by work, which results in a very poor machinability with long and gummy chips, poor surface finish and reduced tool life (Trent, 1989). Existing elements such as chromium, nickel and molybdenum cause high plastic deformation, generating elevated cutting and feed forces. Great shearing forces and high temperatures are also resulting from high rates of cold workability, which can cause surface hardening of workpiece and poor surface finish (Carpenter Tech. Corp., 1987). Those factors contribute for increasing tool wear, accelerated by high cutting forces and elevated temperatures. In addition, required cutting power for such materials determine high machining costs (Lula, 1986). Low thermal conductivity of stainless steels is another harmful characteristic for machining process. In such conditions, generated heat during deformation concentrates in shearing zones raising, significantly, cutting temperatures (Martin and Qcquidant, 1992). Besides, it becomes very difficult to obtain good dimensional tolerances for its high thermal expansion coefficient, mainly in poor cooling conditions. It is important to observe that those difficulties for machining stainless steels are not so significant for ferritic and martensitic types when compared to austenitic and duplex (ferritic + austenitic) (Trent, 1989). Machinability and general characteristics of main groups of stainless steels are listed below (Tab. 2).

Table 2. Machinability and general characteristics of main groups of stainless steels (Carpenter Tech. Corp., 1987).

| **GROUPS** (Main Classes) | **GENERAL CHARACTERISTICS** | **MACHINABILITY** |
|---|---|---|
| **FERRITICS** (AISI 430, 430F, 431, 444) | - Cold workability;<br>- Wide range of corrosion resistance (moderate);<br>- Relatively good ductility. | - Better for low levels of Cr;<br>- Tiny chips and high deformation, specially for higher levels of Cr. |
| **AUSTENITICS** (AISI 303, 304, 304L, 310, 316, 316L) | - High cold hardenability;<br>- Corrosion resistance between good to excellent;<br>- Excellent ductility and toughness. | - Great tendency to produce built-up-edge;<br>- Difficult chip removal (adhering and tiny chip);<br>- Hard machined surface. |
| **DUPLEX** (AISI 318, 325, 329) | - Tensile strength is much higher than the austenitic type, specially with cold deformation;<br>- Excellent corrosion resistance;<br>- Good ductility and toughness. | - Restricted for its high mechanical resistance;<br>- High hardness; |

## 4. Experimental procedure and methodology

Turning tests were carried out in a mechanical lathe IMOR (Fig. 1), 1.5 m length, rotation speeds between 26.5 to 1,400 rpm and power of 10 hp.

For measuring of tool wear – maximum flank wear ($VB_{max}$) – it was used a tool microscope NIKON (Fig. 2) model 12083, magnification of 15X, and an attached micrometer with 1 μm of resolution.

Images of tool wear were registered with a digital cameras SONY model Cyber-shot P92 with 5 megapixels of resolution.

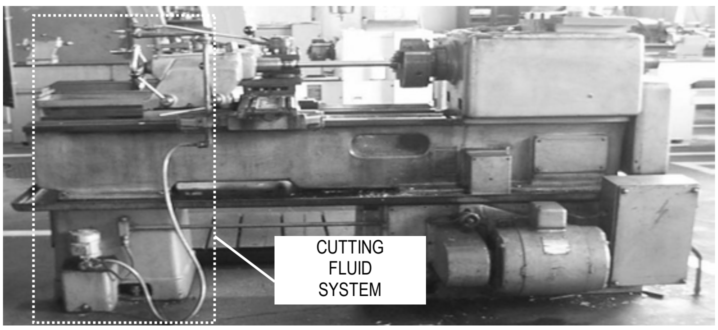


Figure 1. Horizontal mechanical lathe.

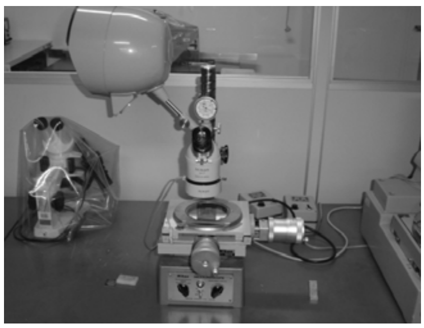

Figure 2 . Tool microscope.

### 4.1. Tool and workpiece material

Workpiece material used in machining tests was an austenitic stainless steel AISI 316 cylindrical bar with 500 mm length initial diameter of 101.6 mm.

Cutting tools were SANDVIK Coromant inserts (Fig. 3) of cemented carbide with a triple coating (TiN, $Al_2O_3$, TiCN) and a geometry WNMG 060408-MM2035 – class M35. The SANDVIK tool holder (Fig. 4) had geometry MWLNR 2020K-06 and the lubricant was the oil Unix 100, manufactured by INGRAX.

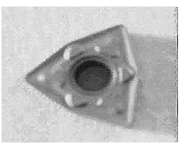

Figure 3. Insert

Figure 4. Tool holder.

### 4.2 Tests and methodology

Tests were carried out in two workpieces beginning from 100 mm diameter and all passes were made along 420 mm length. Table 3 lists the five different cutting speeds that were used, while the others cutting conditions (feed and depth of cut) were kept the same.

Table 3. Cutting conditions

| TEST | $v_c$ (m/min) | f (mm/rot) | $a_p$ (mm) |
|---|---|---|---|
| 1 | 220 | 0.209 | 0.5 |
| 2 | 210 | | |
| 3 | 200 | | |
| 4 | 178 | | |
| 5 | 161 | | |

The first part of investigation employed one workpiece using cutting fluid applied by conventional method (overhead flood), with a flow rate around 150 liters/hr (Fig. 5); same cutting conditions were employed in another workpiece but, at this time, using the NDM method by dropping, with a flow rate around 100 ml/hr (Fig. 6). In both methods, cutting fluid was the same (5% emulsion of mineral soluble oil in water).

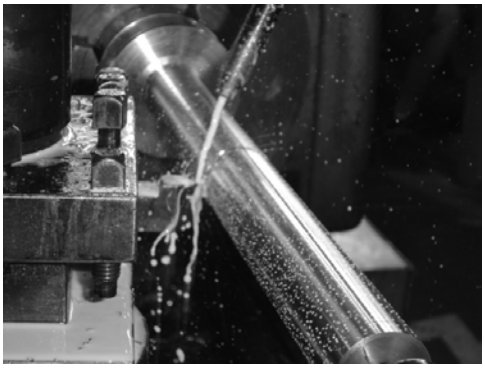

Figure 5. Overhead flood.

Figure 6. NDM method by dropping.

For each cutting speed, maximum flank wear (VBmax – Fig. 7) was measured after each pass of 420 mm length and the values were used to obtain curves for comparison between each investigated method from evaluating tool wear performance.

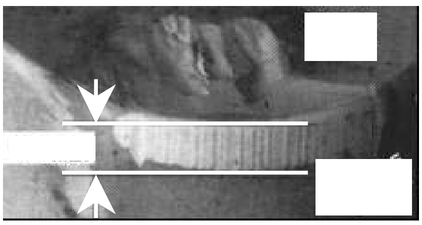

Figure 7. Maximum tool wear ($VB_{max}$)

## 5. Results and discussion

Figures 8 to 12 show a comparison between both cooling/lubricating methods (conventional and NDM) using tool wear behavior for each tested cutting speed. Figure 13 compares, in the same graphic, performance of both methods for all tested machining conditions.

In lowest cutting speed (Fig. 8), NDM was more effective in reducing tool wear rate. This could be explained by lower temperatures levels, which contributed to require a lubricant characteristic of the fluid much more than a cooling role. In this case, thermal wear mechanisms were not significant and NDM provided efficient lubrication enough to reduce tool life even in a temperature slightly higher than in conventional method during all tool life. A small raise in cutting speed (from 161 to 178 m/min – Fig. 9) showed that performance was similar until 15 minutes of tool life, when tool wear rate was accelerated for NDM method. This could be explained by the loss of coating after this time; so, tool lost significant part of its heat resistance and cooling became a required characteristic of cutting fluid, which is better in conventional method.

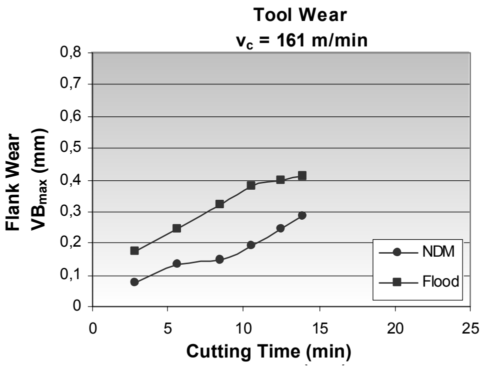


Figure 8. $VB_{max}$ for 161 m/min.

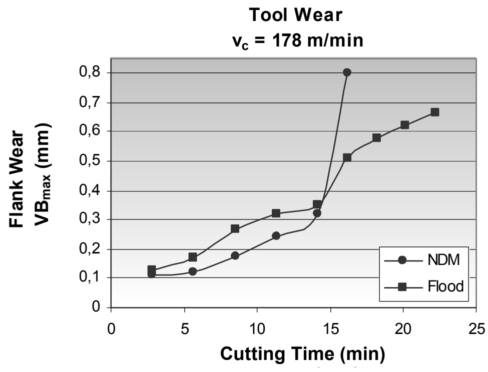


Figure 9. $VB_{max}$ for 178 m/min.

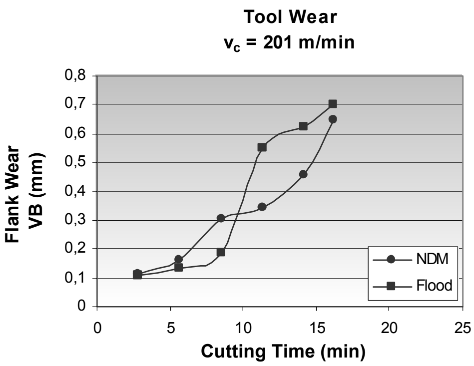


Figure 10. $VB_{max}$ for 201 m/min.

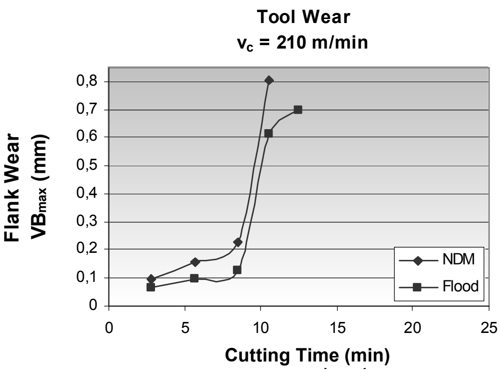


Figure 11. $VB_{max}$ for 210 m/min.

Figure 10 shows that, for cutting speed of 201 m/min, conventional method presented lower wear rates up to 10 minutes of tool life, when happened a change in wear modes with a better performance of NDM method after this time. Considering that cutting temperature became higher for this speed, and the values are too close at the beginning and at the end of curves, probably this is an undefined condition, in which both methods presented similar behavior. Figure 11 presents wear rates measured for 210 m/min. This cutting speed refers to maximum value recommended by tool manufacturer. Once more, it can be detected a very similar wear behavior for both methods during all tool life with a higher rate after 9 minutes. Conventional method is not able to present a cooling performance enough to reduce thermal wear mechanisms as a significant alternative to NDM method. In addition, low thermal conductivity of stainless steel (Gennari and Machado, 1999) contribute to high levels of temperature in cutting zone (Martin and Qcquidant, 1992). In

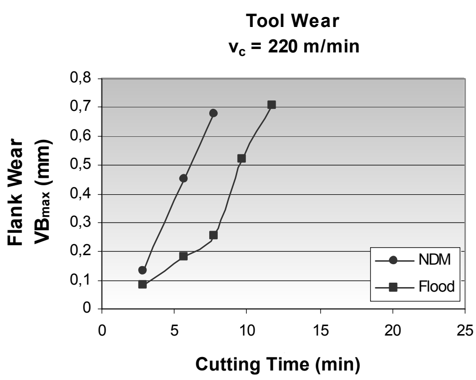


Figure 12. $VB_{max}$ for 220 m/min.

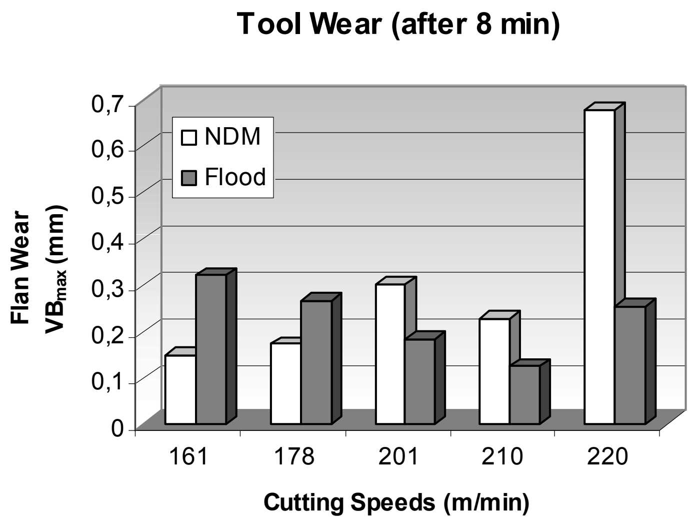


Figure 13. Tool wear after 8 minutes.

NDM method, negative effect of generated heat (tool wear) is much more significant than positive effect (reduction of shearing resistance of workpiece) (Sales *et al.*, 2001). Therefore, since temperatures in NDM are higher than in conventional cooling, tool wear levels tend to be more elevated.

Figure 12 indicates that, for a cutting speed over recommended range, tool wear rates are more accentuated, specially for NDM, because of reduced volume of fluid and, consequently, conventional cooling is more effective.

If one consider a specific tool life (Fig. 13) is possible to observe that values of maximum tool wear were lower when NDM was applied to cutting speeds of 161 and 178 m/min. Those results suggest that lubrication is more effective for lower temperatures, where thermal wear mechanisms are not significant when compared to loss of resistance of workpiece material (Trent, 1989), once the amount of fluid is not enough for cooling such as conventional method. Therefore, generated heat remains in shearing zones, reducing cutting and friction forces, specially normal stresses produced by chip removal. NDM showed similar behavior when compared to flood method for cutting speed of 201 m/min. In this case, one can consider that reduction of fluid is still suitable, once it was not worst than conventional method (Heisel *et al.*, 1998). For higher cutting speeds (210 and 220 m/min) NDM was not so effective, once they characterize severe conditions, requiring a more effective cooling mechanism.

## 6. Conclusion

- ✓ NDM is suitable for turning stainless steels in lower and moderate cutting speeds, considering recommended range by tool manufacturer;
- ✓ In high cutting speeds, generated heat is too elevated so thermal wear mechanisms are severe requiring an effective cooling performance of the system and NDM is not recommended;
- ✓ Cutting speeds slightly over tool application are severe for both investigated methods.

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