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Tarek BRAHAM-BOUCHNAK, Guénaël GERMAIN, Patrick ROBERT, Jean-Lou LEBRUN - High pressure water jet assisted machining of duplex steel: machinability and tool life - International Journal of Material Forming - Vol. Volume 3, n°Issue 1 Supplement, p.507-510 - 2010

High pressure water jet assisted machining of duplex steel: machinability and tool life

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Abstract

High pressure water jet assisted turning (HPWJAT) consists of projecting a high pressure water jet, up to several hundred bar, into the tool-workpiece interface. The water jet is directed between the chip and the tool affording greater protection of the cutting face and better chip breaking. Comparisons are made between assisted turning using several jet pressures and conventional turning with different cutting speeds on the duplex stainless steel, X2CrNiMo22-5. The results show good chip fragmentation and an improvement of tool life with high pressure water jet assistance (HPWJAT). The evolution of the roughness is also investigated. It is shown that it is possible to improve the productivity by using HPWJAT.

INTRODUCTION

Due to environmental and economic constraints, manufacturers look to save time and reduce manufacturing costs.

Stainless steels are extensively used thanks to their excellent physical and metallurgical properties. Hence, the improved machining of these materials requires the use of new processes that make it possible to increase the degree of chip fragmentation to improve the productivity and/or the tool life without reducing the machined surface quality. High pressure water jet assisted turning (HPWJAT) is one of the main methods used for these purposes. Studies have shown that this technique leads to better control of the chip shape [1-3]. With this process it is not only a question of lubricating the cutting zone, but of directing a high pressure water jet between the tool and chip to create a hydrostatic bearing. This improves chip breakage.

Different studies have been carried out to determine the effect of cutting fluids on tool wear mechanisms, chip shapes and surface roughness, obtained after machining [1-5]. The effects of high and ultra-high pressure water jets directed into the tool chip interface on tool temperature, cutting forces, chip shape and surface roughness in turning have been explored by Shet et al [6]. The results show a significant reduction in the tool edge temperature of about 40 to 45%. These authors concluded that the water jet can be used to obtain good heat dissipation to control the chip forming process and to change the cutting process by changing the frictional conditions.

The aim of this study is to highlight the contribution of high pressure water jet assisted machining on a duplex stainless steel (X2CrNiMo 22-5). The material has been prepared and supplied by the company GEA Westafalia Seprator. The increase in productivity is determined by comparing the Taylor experimental curves, with and without high pressure water jet assisted machining.

A comparison is made between the results obtained for low pressure cutting (Classical Lubrication CL) and those obtained with HPWJAT on cutting forces, surface Roughness (Ra and Rmax criteria), and the observation of the tool wear and tool life.

PRESENTATION OF HPWJAT

1 PRINCIPLE

High pressure water jet assistance consists on projecting a high pressure lubricant jet into a specific location of the cutting area (Figure 1). The jet is uni-directional, with a given flow rate and pressure.

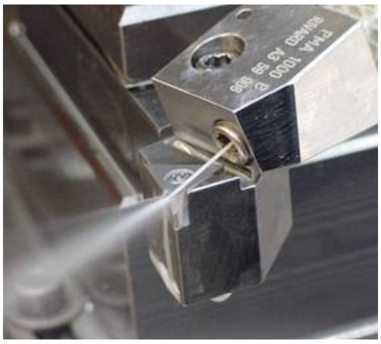

Figure 1: Principle of HPWJAT

This High Pressure (HP) jet allows more effective lubrication and evacuation of the heat produced during the cutting process, as compared to conventional lubrication. The high pressure lubrication adds the possibility of breaking chips by a mechanical action of the jet independently of the cutting parameters. As a result, the high pressure jet can increase significantly the fragmentation of chips for fixed cutting parameters. In addition, under certain conditions the HP water jet can create a film (or a hydrostatic bearing) between the chip and the tool which protects the tool. In this case, the life of the tool can be increased significantly.

2 EXPERIMENTAL EQUIPMENT

The tests were performed on a numerically controlled Ramo lathe, with a horizontal bench and a high-pressure pump Hammelmann HDP42 at 30 kW. The lubricant used is an emulsion of 5% by volume of QUAKERCOOL 7500 SF with water. The emulsion is recommended for very difficult machining of aluminum and hard steel (some stainless steel...).

The HPWJAT tool used was developed in collaboration with SANDVIK SA with a holder reference DNMG 15 06 08 MF (Figure 2).

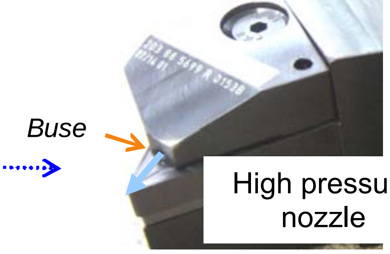

Figure 2: Tool used for high pressure water jet assisted machining test.

The pressure is directly measured in the tool holder by a manometer. The tool is directly posed in a Kistler dynamometer to measure the cutting force during machining.

EXPERIMENTAL STUDY

Tests were conducted using a duplex stainless steel X2CrNiMo22-5 with a hardness of 255 Hv30.

Inserts DNMG 15 06 08 MF (Sandvik) were used and cutting parameters were fixed as follows:

- a feed, f = 0.15 mm.tr^{-1}.
- a cutting depth, ap = 0.5 mm.
- a cutting speed, Vc, which varies depending on the tests to be conducted.

The wear tests were carried out in conventional lubrication and HP water jet assistance. The monitoring cutting force, the surface roughness (Ra and Rmax) and the wear of the inserts (Vb) were investigated during the wear test. Tool life was examined for an average flank wear Vb = 0.1mm.

RESULTS AND DISCUSSIONS

1 CHIP FRAGMENTATION

1.1 Minimal pressure of the assistance

Initial tests were conducted in order to determine the minimum pressure to fragment the chip. Tests were performed with f = 0.15 mm.tr^{-1}, ap = 0.5 mm and Vc = 250 m.min^{-1}, without lubrication, with a classical lubrication (Low Pressure, CL) and then with a HP lubrication up to 450 bar in increments of 50 bar. For each test, with a machining length of about 20 mm, the morphology of the chip was observed (Figure 3).

a) Dry
one long spiral chip

b)Classical Lubrication
one long spiral chip

c) P = 50 bar
Long Spiral Chips
(100mm)

d) P = 100 bar
Long Spiral Chips
(50mm)

d) P = 250 bar
Fragmented Spiral
Chips (10 mm)

e) P = 300 bar
Fragmented Chips
(5mm)

Figure 3: Chip morphology obtained by a) dry machining, b) CL machining and c)-e) HPWJAT

The chip hog from a pressure of 50 bar but the chip length was still too high (about 100 mm) for a good evacuation. The chips present a good fragmentation from a pressure of 250 bar. In this condition, the chips length is about 10mm, therefore this pressure was chosen for testing wear.

1.2 Fragmentation stability

A study of fragmentation stability (P = 250 bar) was conducted by changing the cutting parameters around those fixed. The speed cutting was increased and then decreased by 20%, ditto for the feed speed and the cutting depth. During all these tests, the chip has remained fragmented which leads to assert that fragmentation is very stable in this area (0.4 mm < ap <0.6 mm; 0.12 mm.tr^{-1} < f < 0.18 mm.tr^{-1}, 200 m.min^{-1} < Vc <300 m.min^{-1}).

2 VCMIN DETERMINATION

A COM approach according to the norm ISO DIN 66-520-4 was conducted to determine a minimal cutting speed Vcmin. Indeed, tests in classical lubrication and in HP water jet assistance have been made in increasing the cutting speed from 100 to 450 m.min^{-1} by level of 25 or 50 m.min^{-1}. For each test, the cutting force was measured and the morphology of chips was examined.

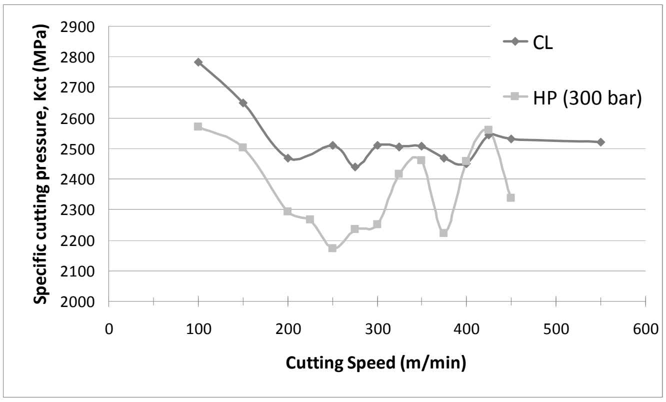

Figure 4: Specific cutting pressure with CL and HP 250 bar.

Figure 4 shows a classic behavior: a decrease of the cutting specific pressure Kc with increasing speed can be noticed, and then a 'stabilization' at a speed named Vcmin is observed. On the contrary, the curve HP (300 bar) presents a large disturbance for cutting speeds higher than 300 m.min^{-1}.

Therefore, a minimum cutting speed Vcmin, can be fixed to 200 m.min^{-1} for tests in Classical Lubrication and 250m.min^{-1} for HP (300 bar).

It could be noted that in classic lubrication and whatever the cutting speed, the chip has never been segmented. However, in HP, chips were always fragmented.

3 WEAR TESTS

The wear tests were conducted at three different cutting speeds with a classical lubrication and a 250 bar HP lubrication. The cutting speeds used are 250, 350 and 450 m.min^{-1} in classical lubrication and 350, 400 and 450 m.min^{-1} in HP 250 bar. A complementary wear test was conducted at 350m.min^{-1} with an HP at 350 bar.

3.1 Result of wear test with CL at 250 m.min^{-1}

Wear tests with classical lubrication were conducted for a criterion wear Vb = 0.1 mm and a cutting speed of 250 m.min^{-1}. The tool life in classical lubrication is 34 minutes. This corresponds to a length machined of 8 500 m.

The surface roughness (Ra and Rmax) remains very stable throughout the test. Indeed, the criterion Ra varies between 0.71 and 1.04µm.

3.2 Comparison of CL and HP tests for a cutting speed of 350 m.min^{-1}

For a cutting speed of 350 m.min^{-1}, the evolution of wear (Vb) with Classical Lubrication and HPWJ at 250 bar is drawn in function of the machining time (Figure 5). These curves allow to determine a tool life (Vb = 0.1 mm) of about 8 min 40s of machining with classical lubrication (CL) and 16 min 45s of machining with 250 bar HP jet, which represents an increase of approximately 93%!

However, It is important to note that a catastrophic wear (Vb increasing very rapidly) appears from a value of Vb = 0.1 mm.

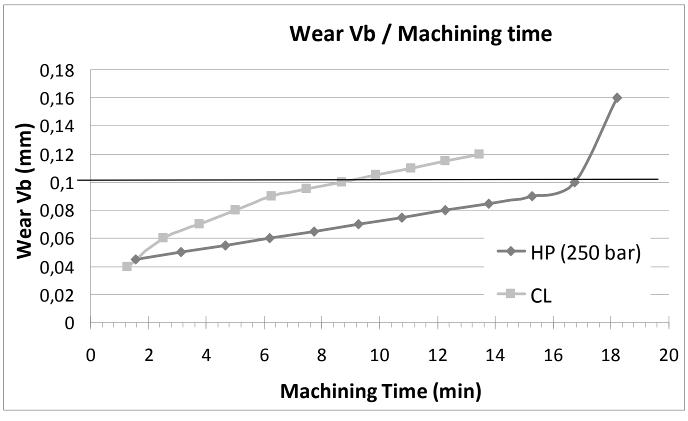

Figure 5: Evolution of the average flank wear with CL and HP at 350m.min^{-1}.

The evolution of the roughness has been drawn and shows a fairly good stability of the criterion Ra according to the wear of the tool (Figure 6).

Indeed Ra remains stable between 0.71 and 1.3 µm whatever the mode of machining (CL or HP). The criterion Rmax, initially fairly stable, at around 4.80 m, increases sharply from 4 000 m machined length for HP machining.

The evolution of the cutting force is identical to the evolution of Rmax.

This is due to the degradation of the tool which appears at 4000m machined length

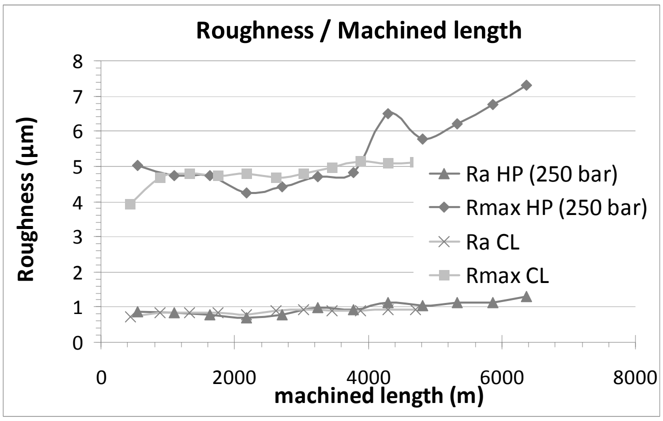

Figure 6: Evolution of the surface state (Ra, Rmax) with CL and HP at 350m.min^{-1}

3.3 Results of wear test in HP at 400 m.min^{-1}

The test wear at 250 bar HP and with a cutting speed of 400 m.min^{-1} shows a linear evolution of wear still a time machine of 8 min (Figure 7), or a machined length of 3 200 m. After this time, wear increases sharply announcing a faster deterioration of the tool. The tool life for this HP 250 bar machining at 400m.min^{-1} is estimated at 9 min 30s.

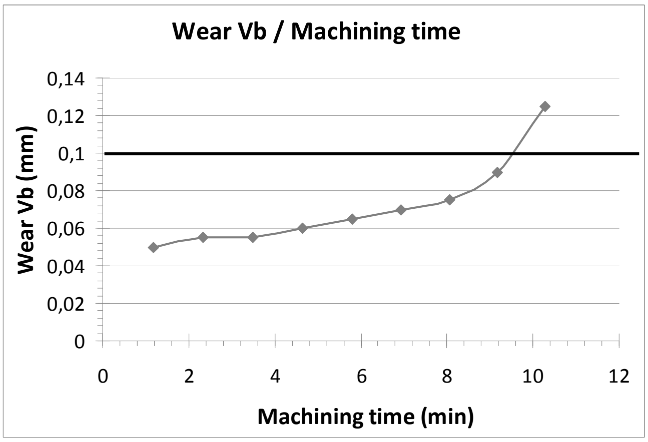

Figure 7: Evolution of the flank wear in HP at 400m.min^{-1}.

The evolution of the surface state shows a good quality (0.51 <Ra <0.89) despite the wear of the tool (Figure 8).

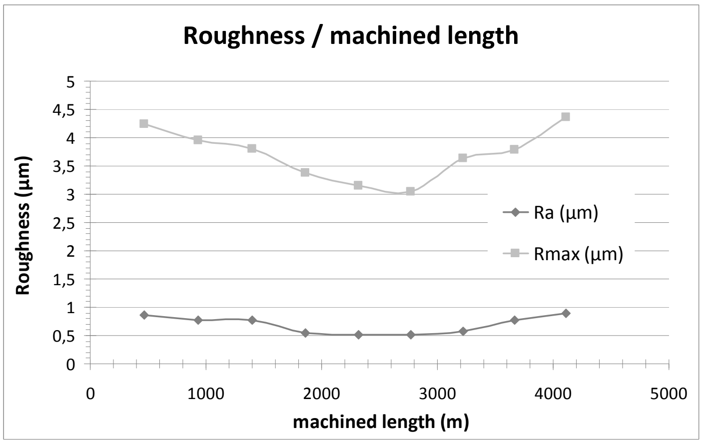

Figure 8: Evolution of surface state in HP at 400m.min^{-1}.

3.4 Comparison of wear tests at 450 m.min^{-1}

For a cutting speed of 450 m.min^{-1}, a CL and a HP wear test have been made. The cutting speed is relatively high, so the tool life is very low. Indeed, on Figure 10, we can estimate the tool life at 2 min 40s with CL and 3 min 30s with 250 bar HPWJ.

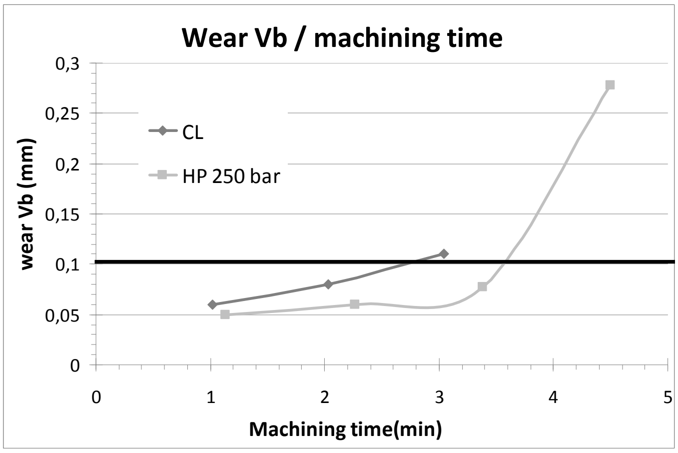

Figure 10: Evolution of flank wear with CL and HP 250 bar at 450m.min^{-1}.

The surface is quite correct for Ra between 0.81 and 1 µm (Figure 11). However, the criterion Rmax increases strongly with the deterioration of the tool.

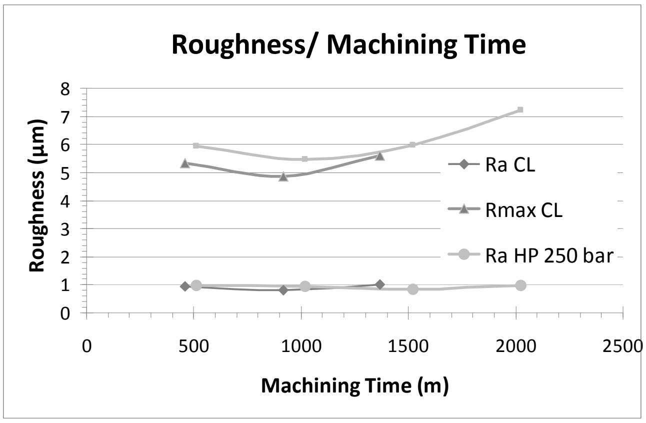

Figure 11: Evolution of Roughness with CL and 250bar HPWJ at 450m.min^{-1}

3.5 Comparison of Taylor Lines

To compare the tools life with classical lubrication and under 250 bar HPWJ, it is interesting to trace the lines of Taylor for these two modes of machining. The results are represented in logarithmic scale on Figure 12.

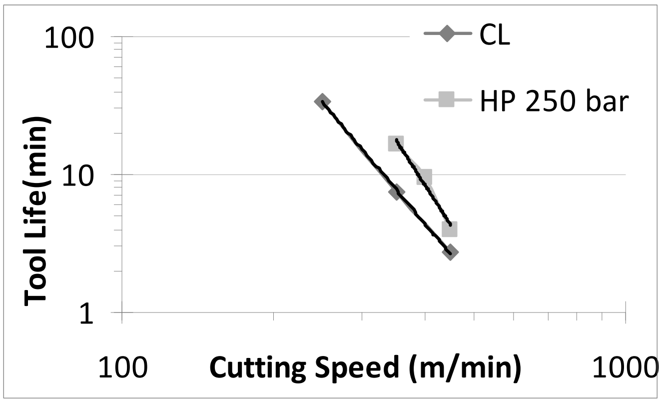

Figure 12: Taylor Lines with CL and HP 250 bar.

Figure 12 highlight a tool life improve with HP water jet assistance. Indeed, gains in tool life are 93% for a cutting speed of 350 m.min^{-1} and about 30% for a cutting speed of 450 m.min$^{-1.}$

It is important to note that the three points for each type of machining, CL and HP 250 bar, are relatively well aligned. This confirms that Taylor model is appropriate for these tests. The equations of Taylor law, for both types of machining, are:

Taylor Law: $\mathbf{T} = \mathbf{C_v}.\mathbf{V^n}$ (1)

With C_v and n constant.
T: tool life (min), V: Cutting speed (m.min^{-1})

In Conventional machining:

$$T_{CL} = 7.638.10^{11}.V_{CL}{}^{-4.302} \quad (2)$$

In High pressure water jet machining at 250 bar, it can be found:

$$T_{HP250} = 4.5604.10^{15}.V_{HP250}{}^{-5.6639} \quad (3)$$

The coefficients of the Taylor Law show, that for a fixed tool life ; the cutting speed can be increased using HP water jet assistance. Indeed, for a tool life of 30 min, the cutting speed should be 260 m.min^{-1} for CL machining and 320 m.min^{-1} with the HP 250 bar, so an increase of the cutting speed of 22% is obtained.

The evolution of tool life as a function of pressure is made on Figure 13.

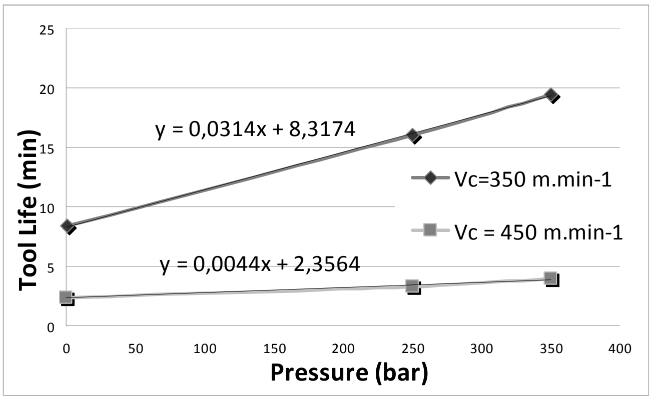

Figure 13: Evolution of Tool life in function of pressure.

We can notice that the evolution of the tool life with the water jet pressure is linear for the two different cutting speeds. The Y-intercept is equivalent to the CL tool life. From these observations, we can propose a modification of the Taylor law in which we take into account the water jet pressure:

Taylor Law modified: $T = C_v.V^n.(A.P+1)$ (4)
with C_v, n, A constants

The surface is the Taylor Law modified. In our case this law is written:

$$T = 7.638.10^{11}.V^{-4.302}.(0.0038.P+1) \quad (5)$$

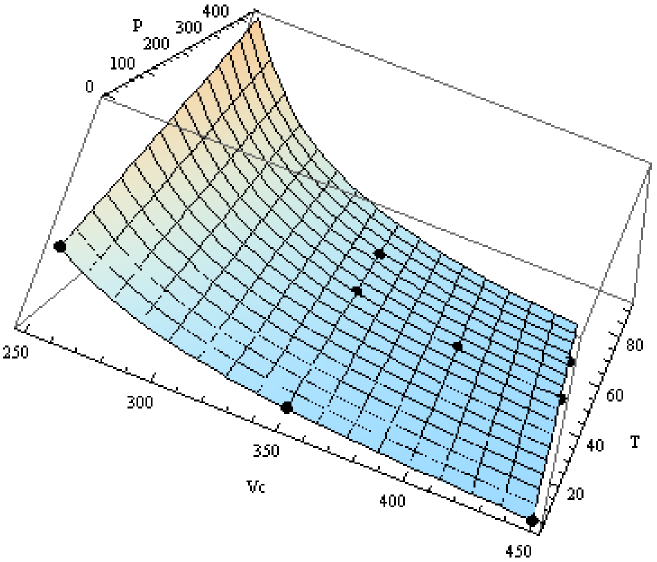

Figure 14: Representation of Taylor law modified and experimental wear tests.

In the figure 14, the surface show the evolution of tool life in function of the cutting speed and the pressure modelled by the Taylor law modified (equation 5) and the black dots correspond to the wear tests results.

It can be noted that there is a good coincidence between experimental points coincide with the modified Taylor law with an error less than 10%. We can therefore conclude that the model predicts well the tool life for different cutting speed and pressure.

The gains due to high pressure are more significant for low-speed cutting, here 250m.min^{-1}. The high pressure water jet serves to reduce the tool-chip contact area. This was evident from the fact that the chip size (which depends upon the tool-chip contact length) is much smaller at higher pressures. This reduced tool-chip contact length consequently serves to alleviate the severe thermal/frictional conditions at tool-chip interface. In the highest cutting speed, it was observed an increase in water pressure was not very beneficial in the tool life. This could be due to the reasoning that a high pressure water jet after penetrating to a certain depth into the tool-chip interface is not capable of penetrating any deeper, overcoming the high contact pressures at the tool-chip interface.

Moreover, the temperature generated by friction in the secondary shearing zone could increase with the cutting speed. The high pressure water jet couldn't dissipate the effective heat in the interface Tool-Chip.

Further investigations need to be carried out to have a better understanding of this phenomenon.

3.6 Interest of a 350 bar pressure on the tool wear

An additional test was conducted with assistance at 350 bar and a cutting speed of 350m.min^{-1}. This test can be directly compared to conventional lubrication test and with assistance of 250 bar (Figure 15).

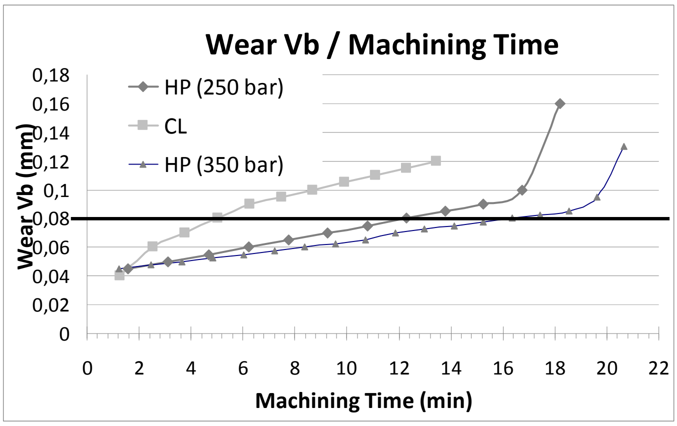

Figure 15: Flank wear evolution with CL, HP 250 bar and HP 350 bar at 350m.min^{-1}

The tool life is estimated to 19 min 45s with the HP 350 bar which represents an increase of 18% compared to an HP 250 bar and a gain of 130% compared to a conventional machining under Classical lubrication.

This latter test shows that the HP water jet assistance is more effective when the pressure is high. The pressure exerted on the tool-chip interface reduces the friction tool-chip (hydrostatic bearing). In this case, higher is the pressure water jet and higher is the protection of the tool. This supposition is in accord with the experimental tests. In fact, for tests with a cutting speed at 350 m.min^{-1} the tool life is measured at: 8 min 40 s in CL, 16 min 45 s with 250 bar HPWJA (+91%) and 19 min 45s with 350 bar HPWJA (+126%).

But, a catastrophic wear appears for lower flank wear. This is due to a tool pick up which appears at the beginning of the catastrophic wear. This pick up can stem from a mechanical action of the water jet which increases the damage of the tool.

CONCLUSION AND OUTLOOK

This study has demonstrated the effectiveness of high pressure water jet assisted machining on a duplex stainless steel (X2CrNiMo 22-5). It is shown that this process results in:

- Increased chip fragmentation in all cutting

conditions.
- Improved productivity with a cutting speed more important.

It was shown that the chips will fragment with a relatively low pressure but it takes a minimum pressure of 200 bar for the chip fragmentation to be suitable for an industrial process.

For a 250 bar pressure, the tool wear is lower compared to CL, so that the tool life is almost double for a cutting speed of 350 $m.min^{-1}$. For a constant tool life, the cutting speed can be increased by about 20% with the HP water jet assistance at 250 bar. This implies increased productivity and a sizable reduction in machine time.

Habak et al [7] studied the effect of high pressure water jet assistance on the residual stresses in austenitic stainless steel. He showed that:

- On the surface, work hardening decreases if HP Water jet Assisted machining is used compared to dry turning.
- HPWJAT makes it possible to decrease the surface tensile stresses. A reduction of the longitudinal residual stresses value by approximately 20 to 40% can be observed.
- The effect of jet pressure on the depth affected by residual stresses and hardening is relatively small.

It is envisaged that the same type of tests (i.e. determination of the residual stress after machining, using X-ray diffraction) will be conducted on the duplex stainless steel, discussed here, in order to determine if the same gains can be observed.

It is expected that the productivity can be further improved with increasing water jet pressure. Further test must be considered to show this.
Similarly, fragmentation tests can also be done to highlight the evolution of the chip splitting zone in a (ap / f) diagram, as a function of water jet pressure.

Acknowledge
This study was undertaken by the *Arts et Métiers ParisTech CER Angers* in collaboration with two industrial partners: CETIM and Westafalia.

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