INFLUENCE OF THE DELIVERY STATE ON MACHINABILITY OF AUSTENITIC STAINLESS STEELS WHEN USING CVD AND PVD COATED TOOLS

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Abstract: Designers of austenitic stainless steel parts do not always specify in detail in what state the work material should be delivered, e.g. annealed or annealed with subsequent cold forming. When a final cold forming step is added there will be an increase in hardness and strength while ductility at the same time is reduced. The mechanical properties of austenitic steels can thus vary significantly and cause unplesant surprises in the machining processes if the delivery state is not clearly specified. The aim of his study is to investigate delivery state effects on two selected machinability criteria; cutting forces and chip breakability. Two different insert grades with the same chip breaker geometry are used, one with a thin physical vapor deposition (PVD) coating and the other one with a thicker chemical vapor deposition (CVD) coating. Both the annealed and the cold drawn delivery states are investigated, and it is shown that cold drawn material gives lower cutting forces for both tool types as well as better chip breakability when combined with the PVD coated tool.

Keywords: 316L, machining, chip formation

1. INTRODUCTION

When machining stainless steels, in a make-to-print manufacturing company, product drawings specify not necessarily the delivery state of the work material in detail while the alloy designation is included. The aim of this study is to investigate whether the state of delivery can affect machinability as limited to the cutting forces and the chip breakability. Improved knowledge in this respect supports the development of sustainable production both from resource and economical points of view.

Austenitic stainless steels are difficult to machine due to their high work hardening rate, the large difference between the yield and the ultimate tensile strength as well as high toughness and ductility. These properties make them prone to built-up edge (BUE) formation, work hardening of cut surfaces, and also poor chip breakability with the increased risk of chip tangling (Kosa and Ney, 1989; Kaladhar, Subbaiah et al., 2012). Previous studies have shown that machinability is influenced by the degree of cold work (Machining operations, 1959), where a small amount can be beneficial as it reduces the tendency to form BUE due to the reduced ductility (Divine, 1975). However, since the strength is increased by the work hardening, tool life tend to decrease and a reduction of the cutting speed might be needed to compensate for this (Machining operations, 1959; Kosa and Ney, 1989). Machinability can also be affected by inclusions, where abrasive particles such as alumina inclusions lower tool life (Faulring and Ramalingam, 1979). However, such particles can be altered by adding controlled amount of calcium and silicon for the dexoidation of the steel, whereby malleable low melting point inclusions results, which increases machinabililty (Bletton, Duet et al., 1990).

In this study, machinability of 316L stainless steel in both the soft annealed condition and in the harder cold drawn condition is evaluated in terms of cutting forces and chip breakability. Round bars were taken from production at a make-to-print manufacturing company. The work material was machinability enhanced by means of the previously described inclusion control (Bletton, Duet et al., 1990), designated UGIMA© 4401, which also fulfils the requirements of AISI 316L.

2. EXPERIMENTAL

The same insert geometry was used for both the cutting force and the chip breakability tests, CCMT060204 with F1 chip breaker from SECO TOOLS AB, with two different grades; TM2000 and CP500. The former is a CVD coated grade ($Ti(C,N) + Al_2O_3$) designed for high cutting speeds in stainless steels and the latter is a tougher PVD coated grade ((Ti, Al)N + TiN). The edge radii of the main cutting edge were measured on all inserts using fringe projection in a GFM MikroCAD. The CP500 inserts used had radii between 22-24 µm and the TM2000 inserts had radii between 37-40 µm. A tool holder from Sandvik Coromant AB was used; SCLCL 1616K 06-S.

2.1. Work material

The mechanical properties of the two batches tested are found in Table 1.

Table 1. Mechanical properties of investigated workpieces.

Delivery state	Diameter of bar [mm]	Yield strength, Rp 0,2% [MPa]	Tensile strength [MPa]	Elongation at break A_{5d} [%]	Hardness (HB)
Annealed	32	293	554	50	159
Cold drawn	25	482	667	41	195

A separate hardness test was performed in order to measure how hardness varied across the diameter. The results can be found in Figure 1. The hardness of the cold drawn bar gradually increased towards the periphery whereas that of the annealed bar did not vary much except for a rather steep final increase near the surface.

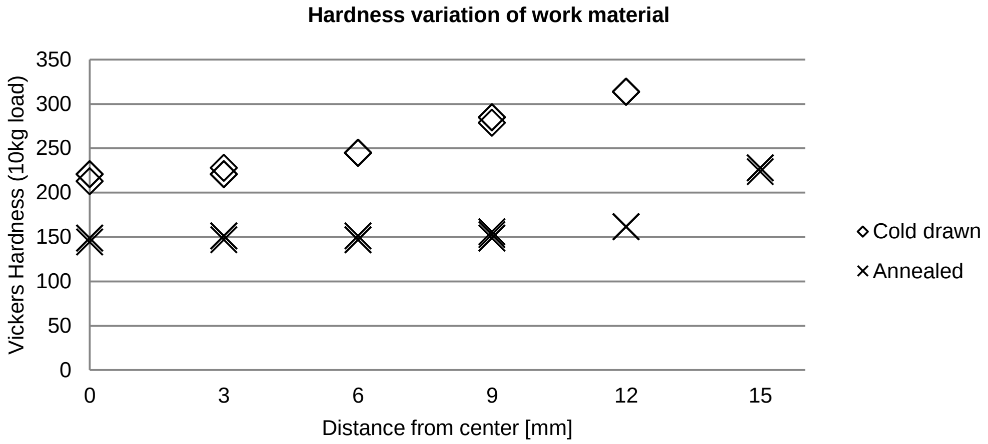

Fig. 1. Hardness variation with the position from the center of the tested work material bars with three indents per radial position.

2.2. Machining set-up

All machining was performed in an EMCO 365 CNC lathe. Cutting fluid was used during all experiments; mineral oil-based emulsion Blaser Swisslube Blasocut BC25-MD with a concentration of 7.5%.

Cutting force measurements.
A three component Kistler type 9275A dynamometer was used for force measurements, see Figure 2. Main cutting force (Fc), feed force (Ff) and passive force (Fp) were recorded. Longitudinal turning was performed at an outer diameter of 24, 20 and 16 mm in both work materials, to avoid influence of machined diameter. This also meant that the hardness variation seen in the annealed material was low. The cutting data used can be found in Table 2. The feed rate was ramped in a stepwise manner from highest value to the lowest at each diameter, resulting in a total of twelve cutting conditions for every cutting edge. The stepwise run of parameters was repeated twice with new inserts for each repetition.

Fig. 2. Machining set-up during cutting force measurements, showing directions of main cutting force (Fc), feed force (Ff) and passive force (Fp).

Table 2. Cutting data used during force measurement.

Cutting Speed [m/min]	150
Feed rate [mm/rev]	0.025, 0.05, 0.10, 0.20
Depth of cut [mm]	2
Entering angle [deg]	95
Rake angle [deg]	0*
Inclination angle [deg]	0*

*Values for tool holder, insert geometry is not included.

Chip breakability.

Longitudinal cuts were taken during chip breakability tests, with an outer diameter of 24 mm, at a constant cutting speed of 150 m/min and depth of cut of 2 and 0.5 mm at four different feed rates; 0.025, 0.05, 0.10 and 0.20 mm/revolution. Cutting fluid was applied during all tests.

3. RESULTS

Markers in graphs represents results from individual replicates whereas lines connects the averaged values of replicates. This applies to all graphs in this section.

3.1. Cutting forces

In order to see whether the difference in hardness and ductility have any influence on cutting forces, the cutting force results for the two work materials are first studied for each tool separately. Figure 3 shows the difference in cutting forces between annealed and cold worked material using the PVD coated grade at the outerrmost diameter investigated, i.e. 24 mm, where the difference in hardness was the highest. At high feed rates it is clear that main cutting forces and feed forces are lower for the cold worked material and that this difference is reduced at lower feed rates.

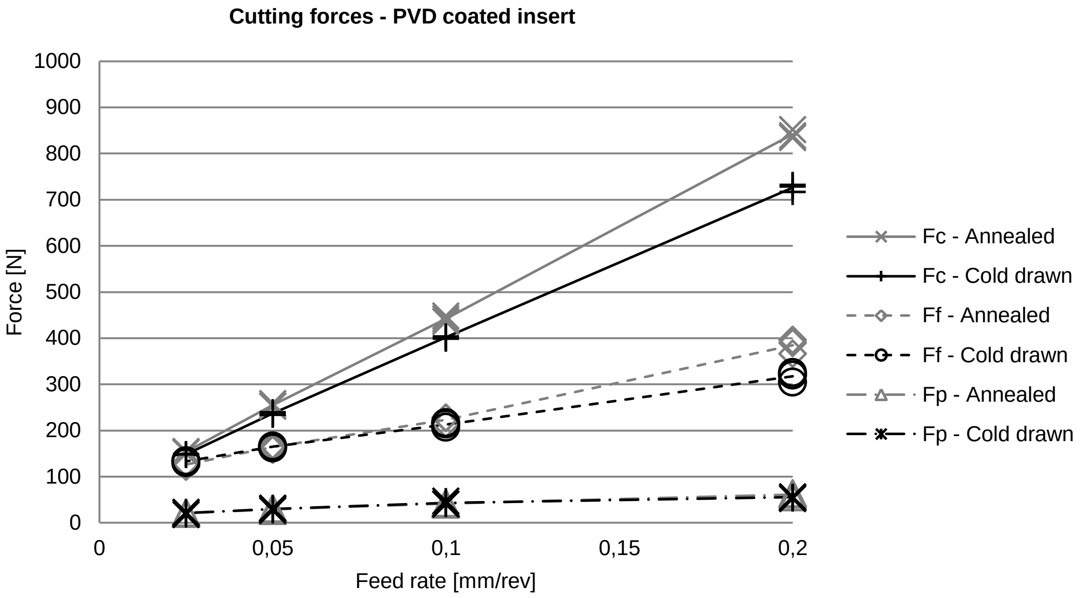

Fig. 3. Cutting forces for the two delivery states when machining with PVD coated inserts at an outer diameter of 24 mm.

The results from tests with the CVD coated tools follow the same trend as the PVD coated tools, with lower cutting forces for the cold worked material, as can be seen in Figure 4.

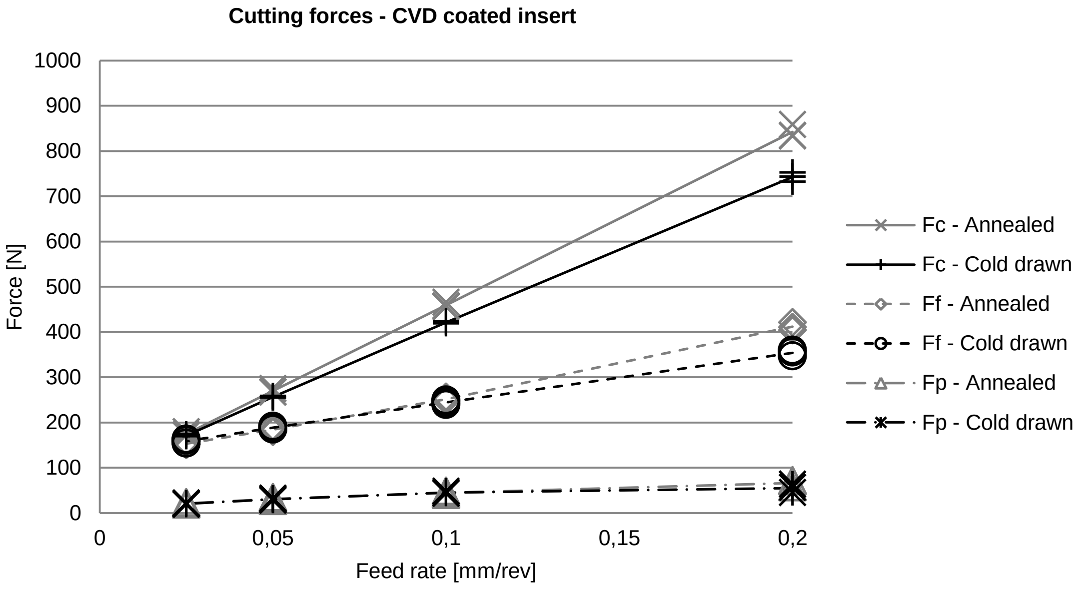

Fig. 4. Cutting forces for the two delivery states when machining with PVD coated inserts at an outer diameter of 24 mm.

Differences between the two grades are shown in Figures 5 and 6. The figures show cutting forces when machining in annealed and cold drawn material respectively. It should be noted that the lowest feed rate of 0.025 mm/rev is lower than the edge radius for the more blunt CVD coated tools (edge radius equal to 37-40 µm) as opposed to the sharper PVD coated tool (edge radius equal to 22-24 µm). The feed forces are generally smaller for PVD coated grade in both work materials, however, the differences in forces are low.

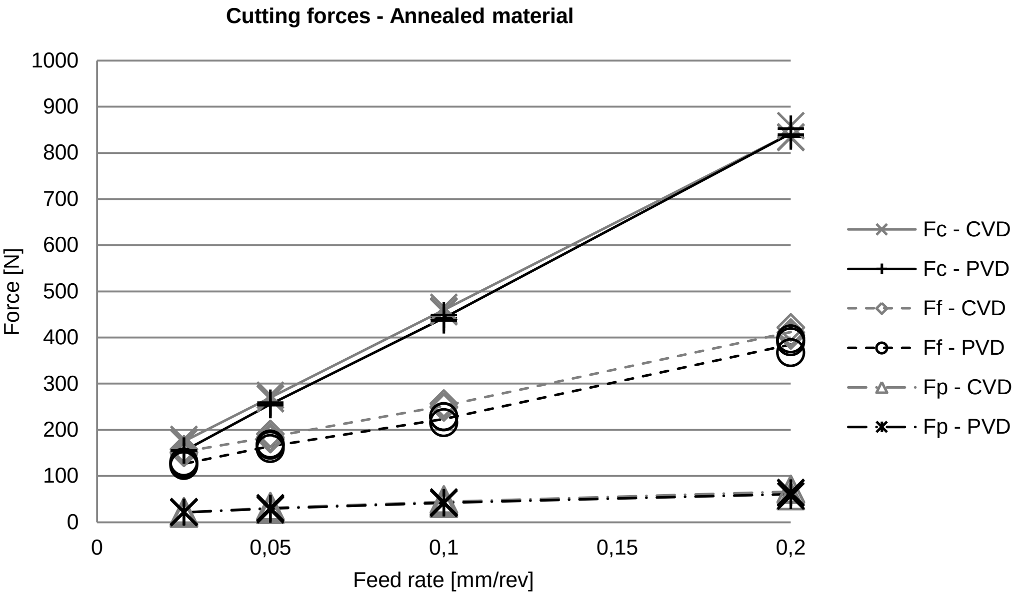

Fig. 5. Cutting forces for the two insert grades (PVD and CVD coated) when machining annealed material at an outer diameter of 24 mm.

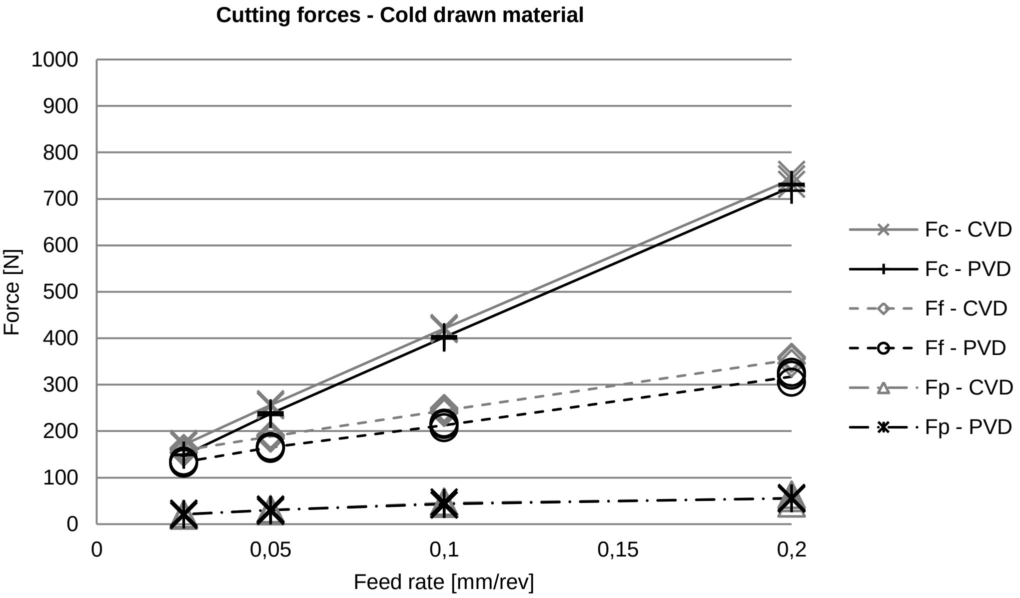

Fig. 6. Cutting forces for the two insert grades (PVD and CVD coated) when machining cold drawn material at an outer diameter of 24 mm.

Figure 7 shows the influence of the hardness variation of the cold worked material on main cutting force and feed force, with respect to the diameter of workpiece. The annealed material with low hardness variation between 16 mm and 24 mm is used as a reference in Figure 8. Forces differ little between the diameters, for both delivery states. Thus, even though the hardness variation is substantial in the cold worked material it seems to have limited influence on the cutting forces.

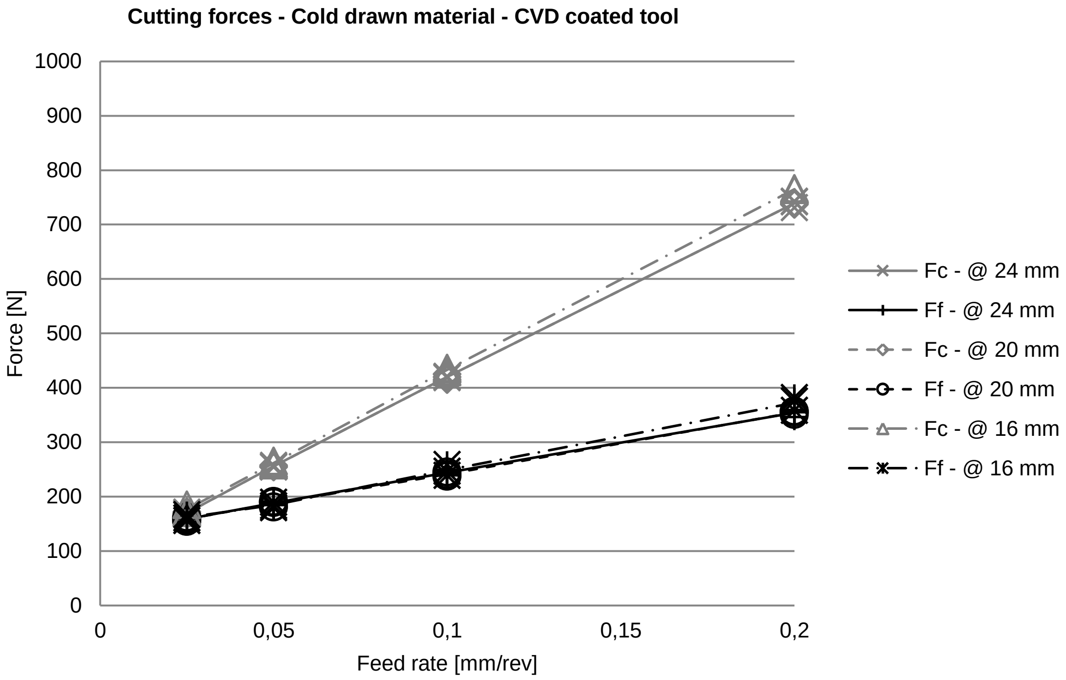

Fig. 7. Cutting forces at three different outer diameters, when machining cold drawn material with the CVD coated grade.

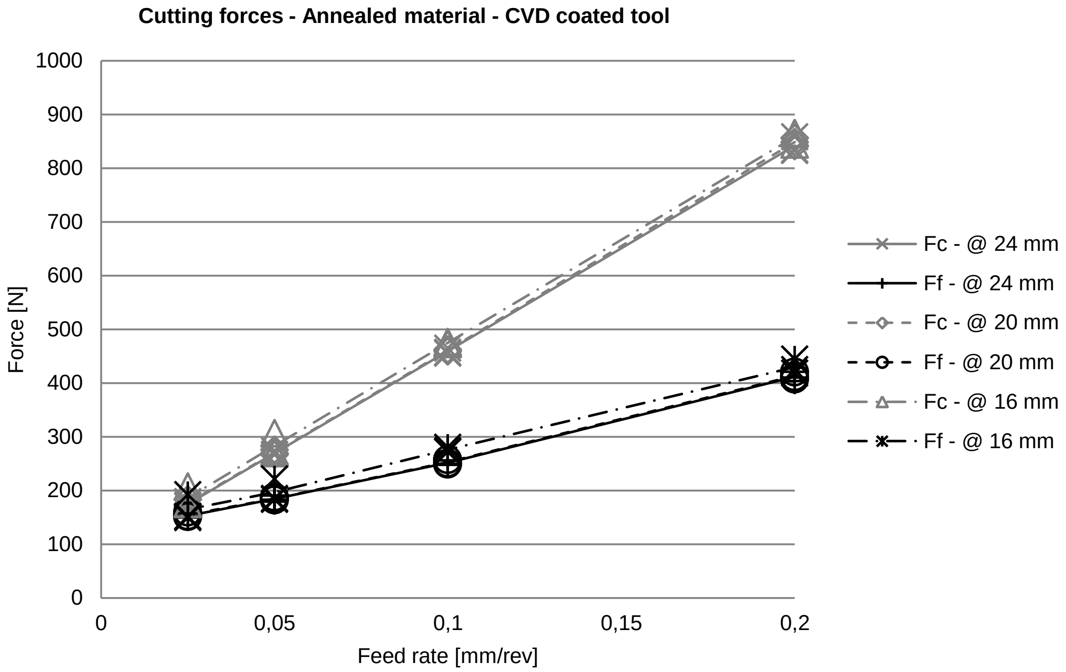

Fig. 8. Cutting forces at three different outer diameters, when machining annealed material with the CVD coated grade.

3.3 Chip breakability

The chip breakability was the same for both materials and insert coatings at the depth of cut of 2 mm. At the depth of cut of 0.5 mm a difference could be found at a feed rate of 0.1 mm/rev, see Figure 9. The PVD coated insert produced short chips, whereas the other combinations of insert and work material had adequate chip breaking at 0.2 mm/rev. Since the properties of the cold worked material varied with diameter the breakability tests were repeated at the outer diameter of 13mm and these showed the same results as for the 24 mm diameter.

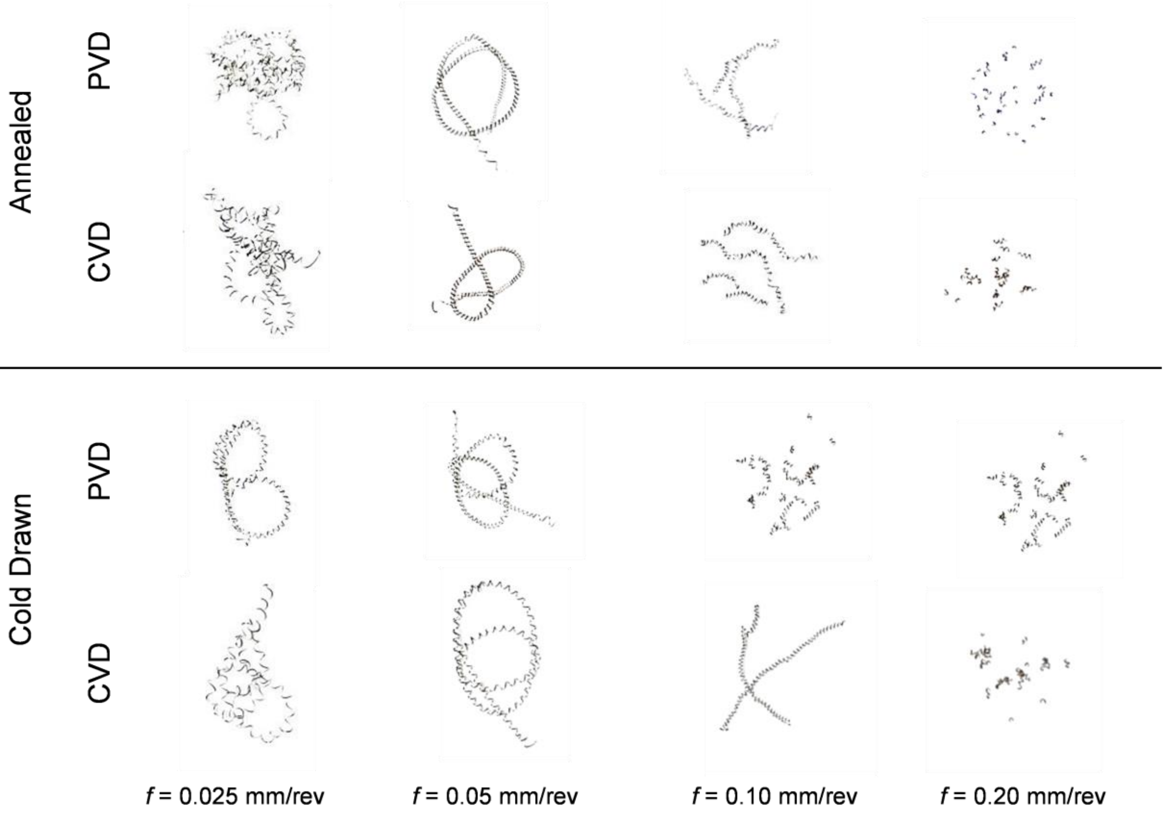

Fig. 9. Results from chip breakability tests when machining with a depth of cut of 0.5 mm.

4. DISCUSSION

When machining 316L bars in cold worked and annealed conditions, cutting forces were shown to be lowest for the cold worked bar. It may seem surpising that harder material induces lower forces during cutting but this can explained by the reduced ductility induced by the cold working operations together with the smaller difference between the tensile and the yield strengths. These effects reduces the amount of plastic work needed to cause rupture (Divine, 1975; Astakhov, 2005). In the present study, the elongation to fracture was 41% for the cold drawn material, while it was 50% for the annealed variant. The difference between tensile and yield strength values was 185 MPa for the cold worked and 261 MPa for the annealed.

There was a small difference in feed force when using the two tool materials tested, for both work materials, where the PVD coated insert gave lower forces. This is most probable due to the thinner PVD coating, which results in a sharper tool as indicated by the cutting edge radius measurements. The two different coating materials, as well as their surface properties could also affect the results, e.g. TiN is considered to have a lower coefficient of friction compared with alumina (AB Sandvik Coromant, 1995). In order to decide whether it is the difference in tool geometry or the coating properties that explain the differences, tests have to be performed where these factors are separated.

The hardness gradient in the cold drawn material had little influence on cutting forces and chip breakability in contrast to differences found for these characteristics between the cold drawn and annealed materials. The gradient has been addressed earlier and is more severe in large diameter bars than in small diameter bars (Divine, 1975). Presently we do not have any explanation for these anomalous results.

Chip breaking have previously been reported to improve when cold forming the material (Machining operations, 1959). In the current study the ductility difference between the cold drawn material (41% elongation to fracture) and the annealed material (50%) is not remarkable.There was only improvement of breakability when using the PVD coated tool.

The differences found between the delivery states of the two work materials seem to favour the cold drawn condition, both in terms of better chip breakability, when combined with the PVD insert, as well as lower cutting forces. However, as has been discussed earlier, the increased hardness might have a negative effect on tool wear, although it has also been reported to lack such effect on tool wear (Clark, 1964). The cold worked materials have also been described to "move" during machining due to the highly strained matrix, resulting in a negative effect on dimensional accuracy. This can sometimes be solved by stress-relieving the part before machining (Divine, 1975).

5. CONCLUSIONS

- Both the main cutting forces and the feed forces were lower for the cold drawn material, especially at the highest feed rate of 0.2 mm/rev.
- The PVD coated inserts gave lower feed forces than the CVD coated inserts.
- The diameter had little influence on cutting forces and chip breakability, although hardness was found to increase substantially with the position from the center in the cold worked material.
- Chip breaking was better in the cold worked material when using PVD coated inserts.

6. ACKNOWLEDGEMENTS

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REFERENCES

AB Sandvik Coromant (1995). Modern skärande Bearbetning, en praktisk handbok. Sandviken, Idéreklam.

Astakhov, V. P. (2005). "On the inadequacy of the single-shear plane model of chip formation." *International Journal of Mechanical Sciences* **47**(11): 1649-1672.

Bletton, O., R. Duet and P. Pedarre (1990). "Influence of oxide nature on the machinability of 316L stainless steels." *Wear* **139**(2): 179-193.

Clark, W. C. (1964). "Which free-machining stainless?" *Metalworking Production*: p. 43-45.

Divine, C. A. J. (1975). "What to Consider in Choosing an Alloy." *Machining Stainless Steels, American Society for Metals*: p. 91-95.

Faulring, G. and S. Ramalingam (1979). "Oxide inclusions and tool wear in machining." *Metallurgical Transactions A* **10**(11): 1781-1788.

Kaladhar, M., K. V. Subbaiah and C. H. S. Rao (2012). "Machining of austenitic stainless steels - a review." *International Journal of Machining and Machinability of Materials* **12**(1): 178-192.

Kosa, T. and R. P. Ney (1989). Machining of Stainless Steels. Metals Handbook Vol. 16 Machining, 9th ed.

Machining operations (1959). "Stainless Steel Fabrication." *Allegheny Ludlum Steel Corporation*: p.223-259.