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Hybrid Machining versus Hard Turning- Investigation on Process Induced Residual Stresses

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Abstract: Thermally-cryogenically assisted machining (TCAM), also known as Hybrid machining, which consists of a combination of hot machining and cryogenic machining processes is one of the attractive machining techniques for today's industry. Previous works attested that TCAM improves tool life and reduces cutting forces and chatter vibrations. However, in spite of its significant influence on in-service part performance and fatigue life, a little concern has been given to the TCAM induced residual stresses. This paper discusses the residual stress distribution on hardened D2 tool steel machined by TCAM and hard turning (HT) using PCBN cutting tools. The results showed that TCAM induces larger compressive area and larger maximum compressive stress levels below the machined surface comparatively to HT. When the cutting speed is increased, surface residual stresses tend to be tensile and the compressive residual stress depth is increased particularly in the case of TCAM.

Keywords: Hybrid machining, turning, hardened steel, PCBN, Residual stresses.

1. INTRODUCTION

Over the last decades, many advanced machining techniques have been developed in order to improve the machining of hard-to-cut materials. In fact, the poor machinability of such materials is related to their high strength, high hardness and to the tendency for high strain-hardening during machining. Thermally assisted machining (hot machining) becomes an alternative to conventional machining of hard-to-cut materials since the flow stress and strain hardening rate of materials decrease with increasing temperature [Sun *et al.*, 2010]. Many previous study attested that hot machining may results to longer tool life [Ginta *et al.* 2009], reduces cutting forces [Sun *et al.*2008] [Jomaa et al., 2011] and produces smoother machined surfaces [Dandekar *et al.* 2010]. However, over heating the workpiece material has less or negative influence on the reduction in tool wear [Yang *et al.*, 2008] [Tian *et al.*, 2008]. Previous works reported that hot machining induces lower compressive residual stresses [Germain *et al.*, 2006] or tensile residual stresses [Germain *et al.*, 2008] and phase transformation [De Lacalle *et al.*, 2004]. Hence, it is clear that more effective methods for enhancing the chip formation process and cooling the cutting tool without affecting the heating of the workpiece are needed [Sun *et al.,* 2010]. In fact, many studies attested that the use of cryogenic cooling during machining may reduces tool wear and cutting forces [Yildiz *et al.,* 2008] , induces thicker compressive zone beneath the surface and reduces or preventing phase transformation [Kenda *et al.,* 2011] [Umbrello *et al.,* 2011] [Pu *et al.,* 2011]. Recently, a thermally-cryogenically assisted machining, well known "hybrid machining", is developed in order to overcome the disadvantages of hot machining and to benefit from the contribution of the cryogenic machining [Wang *et al.,* 2003] [Dandekar *et al.,* 2010] [Jomaa et al., 2011]. Nevertheless, most works focused on the machinability aspect when thermally-cryogenically machining is performed and a little concern has been given to the surface integrity and particularly to the machining induced residual stresses.

Actually, the residual stresses are among the most significant quality-related performance output in machining processes. Hence, to be a viable and attractive technique, hybrid machining should be designed in a way to improve both the machinability aspects and surface integrity characteristics as well, specifically, the residual stresses. Therefore, the present work attempted to investigate the residual stresses induced by thermally-cryogenically assisted machining of hardened AISI D2 cold work tool steel (59-61 HRC) using PCBN cutting tool. The experimental results for hybrid machining are compared to those for conventional hard turning obtained under similar cutting conditions.

2. EXPERIMENTS

The thermally-cryogenically assisted machining (TCAM) investigated in this work (Figure 1) consists of preheating the workpiece before turning operations and cooling the cutting tool/chip contact zone by liquid nitrogen jet during machining, i.e., cryogenic cooling, LN2.

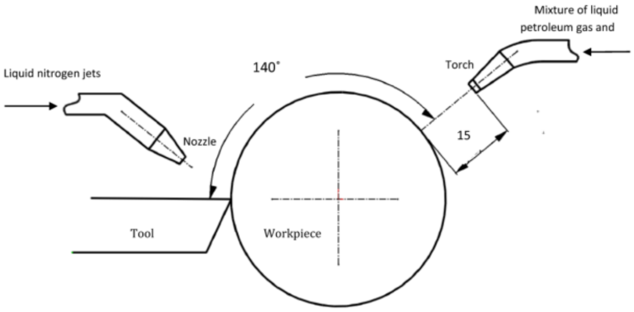

Figure 1; Thermally-cryogenically assisted machining; TCAM design

A torch, burning a mixture of liquid petroleum gas and oxygen, was used as a heating source in TCAM experiments. The temperature was about 450°C and measured using a thermocouple type-K. Chamfered and honed PCBN inserts (CB 7020) with a square geometry and has an effective rake angle, γe = -28°, were used in the experiments. The workpiece material was AISI D2 tool steel hardened and tempered to 59-61 HRC.

The specimens were machined at varying cutting speed (50, 100 and 150 m/min) and at fixed feed (0.05 mm/rev) and depth of cut (0.25 mm) for both HT and TCAM. X-ray diffraction technique was used to measure the residual stress distributions. The measurements were performed accordingly to the ASTM E1426-91 standard. Cutting forces were measured using a 3-component force Kistler dynamometer and machined surface texture was analyzed using a scanning electron microscope (SEM).

3. RESULTS

The residual stress distributions induced by TCAM and HT in axial and circumferential directions are shown in Figure 2. Only average values are used in the plots for better lisibility. It is evident that the residual stress depth profiles differ between hoop (Figure 2-a) and axial directions (Figure 2-b). The residual stress distributions show compressive stresses in the workpieces machined with tested processes.

When TCAM was performed, both in-depth maximum stress level and compressive stress aerea were significantly increased compared to HT. Besides, surface residual stresses were compressive in the two measured directions. Surface residual stresses varied from -254 MPa to 157 MPa for HT and from -398 MPa to -58 MPa for TCAM, depending on the measured direction and cutting speed (Figure 3). In fact, when cutting speed was increased, two phenomena occurred: Firstly, surface residual stresses tend to be tensile. Secondly, the pick position and the affected zone depth were increased particularly for TCAM.

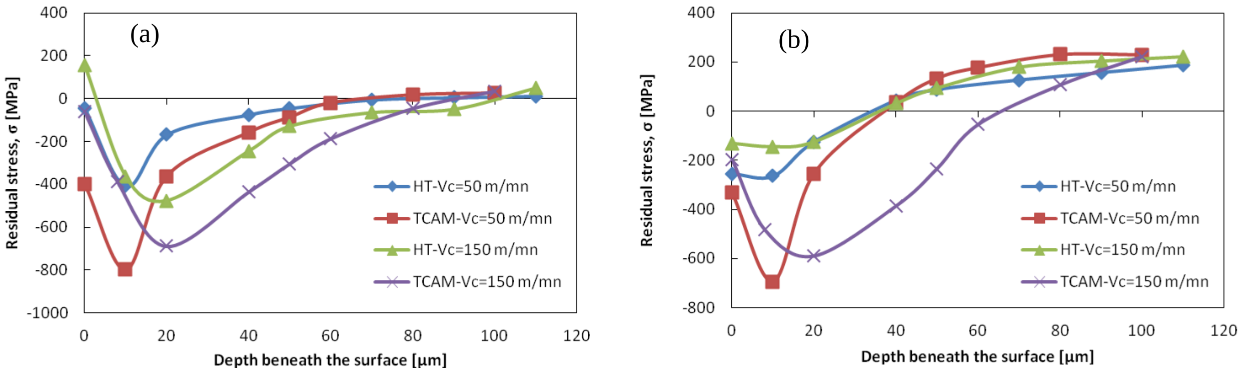

Figure 2; Effect of machining processes on a) circumferential and b) axial residual stresses at feed of 0.05 mm/mn and depth of cut of 0.25 mm

It is generally agreed that the residual stresses are one of the most relevant characteristics of surface integrity that affects significantly the structural components life and performance. Specifically, several studies found that tensile residual stress reduced fatigue strength and compressive residual stress improved it [Hashimoto *et al., 2006*]. It should be mentioned, here, that the results presented above are valuable since they shows that larger compressive residual stress levels can be generated during TCAM of AISI D2 cold work tool steel. The TCAM seems to be an adequate machining technique that may enhance the in-service part life by inducing a large compressive residual stresses compared to HT.

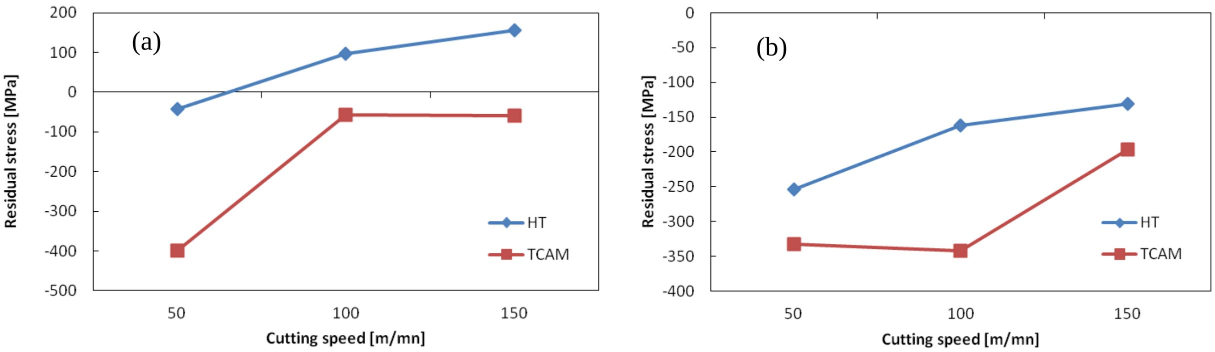

Figure 3; Effect of cutting speed on a) circumferential and b) axial residual stresses at feed of 0.05 mm/mn and depth of cut of 0.25 mm

4. DISCUSSION

Analysis of the results referred to residual stresses induced by machining will be discusses here in terms of machining process, cutting forces and surface defects. Special attention will be given to the workpiece/process interaction.

4.1 Effect of machining process

Several parameters can explain the compressive residual stresses (at the surface and below machined surface) generated by machining. As we mentioned previously, the cutting tool used is a low CBN content cutting tool with the negative effective rake angle (-28°). Several works claimed that the greater negative effective rake angle and the use of chamfer plus hone radius insert induces a large compressive residual stresses [Dogra *et al.*, 2011]. Besides, machining a high hardness materials (HRc 59-61) with such cutting tool edge preparation promote the generation of compressive residual stresses [Thiele *et al.*,2000]. In fact, with the use of the chamfered tool, a very strong compressive deformation state on the cutting edge. Thus, the burnishing process becomes a dominant factor in chip formation due to the squeezing of the material under the cutting edge which builds up severe elastic and plastic deformation in the machined surface resulting in larger compressive residual stresses [Hua *et al.*, 2005]. Since the work material were preheated in TCAM, the cutting temperature will be high enough to favour chip formation by plastic deformation rather than fracture resulting in reduced cutting forces and so increased compressive residual stresses at the surface, comparatively to HT (Figure 4).

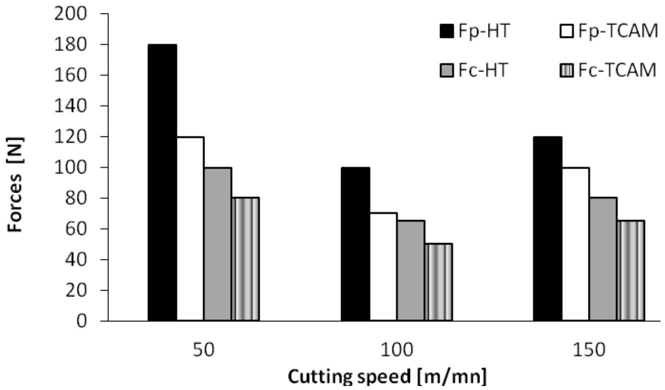

Figure 4; Effect of cutting speed on cutting forces at feed of 0.05 mm/mn and depth of cut of 0.25 mm; Fp: thrust force, Fc: main cutting force

The observed differences between residual stress levels induced by TCAM and HT are largely in part due to the cryogenic cooling and heating temperature (450°C). Specifically, the liquid nitrogen jet seems to play an important role in preventing or reducing heat accumulation in cutting zone by providing better cooling effectiveness and suitable cutting temperature, and reducing friction [Hong *and Ding,* 2001] [Hong *et al.,*2001]. The results are in a good agreement with those obtained by [Ben Fredj *et al.,* 2006] [Umbrello *et al.,*2011] [Pu *et al.,*2011] who demonstrated that cryogenic cooling increases the compressive area of machined components and reduces the white layer thickness.

4.2 Effect of cutting speed

Surface residual stresses tend to be tensile when the cutting speed is increasing to 150 m/mn specifically for HT. In fact, when increasing the cutting speed the friction energy increases too. Thus, high amount of heat is introduced into the workpiece leading to the white layer and/or microcracks formation at the surface which are usually associated with tensile residual stresses particularly in HT (Figure 5). This correlation is in agreement with results reported by [Schwach *et al.,* 2005].

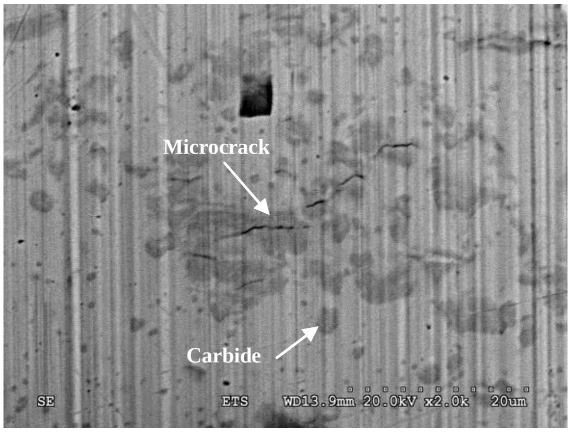

Figure 5; Hard turning induced microcracks on the machined surface at cutting speed of 50 m/mn, feed of 0.05 mm/mn and depth of cut of 0.25 mm

However, in contrast of HT, surface residual stresses still of compressive one even though of speed increase in the case of TCAM. This may be explained by the prominent role played by the cryogenic cooling in regulating the cutting temperature and consequently decreasing the thermal effect and reducing the tendency for producing tensile residual stresses [Kenda *et al.*,2011]. Nevertheless, the effectiveness of the cooling effect depended significantly on the aerodynamic conditions around the cutting zone. At lower cutting speed the tool/chip contact is practically elastic and liquid nitrogen is dragged in that elastic contact zone by capillarity effect and is likely to enable more effective cooling [Dhar *et al.*,2002]. However, with the increase in cutting speed the chip makes fully plastic or bulk contact with the tool rake surface and prevents the fluid from entering into the hot tool/chip interface which accentuates the thermal effect. Additionally, further increase of the cutting speed induces; first, intense turbulent air flow by the faster workpiece motion which may prevent the nitrogen jet from reaching the tool/chip interface [Jomaa et al., 2011]. Second, the cooling process may not get enough time to remove the heat accumulated at the cutting zone resulting in less reduction of the temperature under cryogenic cooling at higher cutting speed and hence resulting to decreased compressive residual stresses.

The results obtained in HT supports previous findings by [Arsecularatne *et al.,* 2006] who affirmed that the hard machining of the AISI D2 steel at speeds higher than 140 m/mn are not viable in the interest of tool life. It is shown in the present work that is not also viable in the interest of residual stresses. However, the use of thermally-cryogenically assisted machining could be an attractive process to increase the tool life, reduces cutting forces [Jomaa et al., 2011] and improve the surface integrity of hardened steels (residual stresses) at higher cutting speed thus offering potential for high speed machining better than conventional hard turning.

CONCLUSIONS

In this work, the effect of thermally-cryogenically assisted machining and hard turning on the residual stress distribution was discussed experimentally. The results show that thermally-cryogenically assisted machining results to larger compressive area, larger compressive residual stresses (at the surface and below machined surface) compared to hard turning. Besides, by controlling the cryogenic cooling and heating temperature, it is possible to generate tailor-made stresses (Maximum stresses occurred both for the levels and for the depth) in the product by thermally-cryogenically assisted machining technique. The use of thermally-cryogenically assisted machining can improve surface integrity and consequently, may results to improved fatigue life and in-service performance of machined high strength structural materials.

REFERENCES

[Arsecularatne et al., 2006] Arsecularatne, J. A., L. C. Zhang , C. Montross & P. Mathewc; ”On machining of hardened AISI D2 steel with PCBN tools”. *Journal of Materials Processing Technology,* (2006) 171**,** 244.

[Ben Fredj et al., 2006] Ben Fredj, N., H. Sidhom & C. Braham; " Ground surface improvement of the austenitic stainless steel AISI 304 using cryogenic cooling" *Surface and Coatings Technology* (2006), 200**,** 4846-4860.

[Dandekar et al., 2010] Dandekar, C. R., C. Shin & J. Barnes; "Machinability improvement of titanium alloy (Ti–6Al–4V) via LAM and hybrid machining" *International Journal of Machine Tools and Manufacture* (2010), 50**,** 174-182.

[De Lacalle et al., 2004] De Lacalle, L. N. L., J. A. Sa´ nchez, A. Lamikiz & A. Celaya; "Plasma assisted milling of heat-resistant superalloys" *Journal of manufacturing science and engineering* (2004), 126**,** 274.

[Dhar et al., 2002] Dhar, N. R., S. Paul & A. B. Chattopadyay; "The influence of cryogenic cooling on tool wear, dimensional accuracy and surface finish in turning AISI 1040 and E4340C steels" *Journal of Materials Processing Technology* (2002), 123**,** 483-489.

[Dogra et al., 2011] Dogra, M., V. S. Sharma & J. Dureja; " Effect of tool geometry variation on finish turning–A Review" *Journal of Engineering Science and Technology Review* (2011), 4**,** 1.

[Germain et al., 2008] Germain, G., J. L. Lebrun, T. Braham-Bouchnak, D. Bellett & S. Auger; "Laser-assisted machining of Inconel 718 with carbide and ceramic inserts" *International journal of material forming* (2008), 1**,** 523.

[Germain et al., 2006] Germain, G., F. Morel, J. L. Lebrun, A. Morel & B. Huneau; "Effect of Laser Assistance Machining on Residual Stress and Fatigue Strength for a Bearing Steel (100Cr6) and a Titanium Alloy" *MATERIALS SCIENCE FORUM* (2006), 524/525**,** 569-574.

[Ginta et al., 2009] Ginta, T. L., A. K. M. N. Amin, M. A. Lajis, A. N. M. Karim & H. C. D. M. Radzi; " Improved tool life in end milling Ti-6Al-4V through workpiece preheating" *European Journal of Scientific Research* (2009) 27**,** 384–391.

[Hashimoto et al., 2006] Hashimoto, F., Y. B. Guo & A. W. Warren; " Surface Integrity Difference between Hard Turned and Ground Surfaces and Its Impact on Fatigue Life" *CIRP Annals - Manufacturing Technology* (2006), 55**,** 81-84.

[Hong et al., 2001] Hong, S. Y. & Y. Ding; "Cooling approaches and cutting temperatures in cryogenic machining of Ti-6Al-4V" *International Journal of Machine Tools and Manufacture* (2001), 41**,** 1417-1437.

[Hong et al., 2001] Hong, S. Y., Y. Ding & W. Jeong; "Friction and cutting forces in cryogenic machining of Ti-6Al-4V" *International journal of machine tools & manufacture* (2001), 41**,** 2271.

[Hua et al., 2005] Hua, J., R. Shivpuri, X. Cheng, V. Bedekar, Y. Matsumoto, F. Hashimoto & T. R. Watkins; "Effect of feed rate, workpiece hardness and cutting edge on subsurface residual stress in the hard turning of bearing steel using chamfer+hone cutting edge geometry" *Materials Science and Engineering: A* (2005), 394**,** 238-248.

[Jomaa et al., 2011] Jomaa, W., N. Ben Fredj, I. Zaghbani & V. Songmene; "Non-Conventional Turining of Hardened AISI D2 Tool Steel" *International Journal of Advances in Machining and Forming Operations* (2011) Vol.3 93-126.

[kenda et al., 2011] Kenda, J., P. Franci & K. Janez; ”Analysis of Residual Stresses in Sustainable Cryogenic Machining of Nickel Based Alloy—Inconel 718” *Journal of manufacturing science and engineering* (2011), 133**,** 041009.

[Pu et al., 2011] Pu, Z., J. C. Oteiro, A. C. Batista, O. W. Dillon Jr, D. A. Puleo & I. S. Jawahir; ”Surface Integrity in Dry and Cryogenic Machining of AZ31B Mg Alloy with Varying Cutting Edge Radius Tools” *Procedia Engineering* (2011), 19**,** 282.

[Schwach et al., 2005] Schwach, D. W. & Y. B. Guo; ”Feasibility of producing optimal surface integrity by process design in hard turning” *Materials science & engineering. A, Structural materials: properties, microstructure and processing* (2005), 395**,** 116.

[Sun et al., 2010] Sun, S., M. Brandt & M. S. Dargusch; ” Thermally enhanced machining of hard-to-machine materials—A review” *International Journal of Machine Tools and Manufacture* (2010), 50**,** 663-680.

[Sun et al., 2008] Sun, S., J. Harris & M. Brandt; ”Parametric Investigation of Laser-Assisted Machining of Commercially Pure Titanium” *Advanced engineering materials* (2008), 10**,** 565.

[Thiele et al., 2000] Thiele, J. D. & S. N. Melkote; ”Effect of cutting edge geometry and workpiece hardness on surface residual stresses in finish hard turning of AISI 52100 steel” *transaction of ASME , Journal of Manufacturing Sciences and Engineering* (2000), 122.

[Tian et al., 2008] Tian, Y., B. Wu, M. Anderson & Y. C. Shin; ” Laser-assisted milling of silicon nitride ceramics and Inconel 718” *Journal of manufacturing science and engineering* (2008), 130**,** 031013.

[Umbrello et al., 2011] Umbrello, D., Z. Pu, S. Caruso, J. C. Oteiro, A. D. Jayal, O. W. Dillon Jr & I. S. Jawahir; ”The effects of Cryogenic Cooling on Surface Integrity in Hard Machining” *Procedia Engineering* (2011), 19**,** 371.

[Wang et al., 2003] Wang, Z. Y., K. P. Rajurkar , J. Fan , S. Lei , Y. C. Shin & G. Petrescu; ”Hybrid machining of Inconel 718” *International journal of machine tools & manufacture* (2003), 43**,** 1391.

[Yang et al., 2008] Yang, B. & S. Lei; ”Laser-Assisted Milling of silicon nitride ceramic: a machinability study” *International Journal of Mechatronics and Manufacturing Systems* (2008), 1**,** 116.

[Yildiz et al., 2008] Yildiz, Y. & N. Muammer; ”A review of cryogenic cooling in machining processes” *International journal of machine tools & manufacture* (2008), 48**,** 947.