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Technical note

In situ surface hardening during turning *via* pyrolytic carburization

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ABSTRACT

This paper describes the application of a carbonaceous feed gas (acetylene with a nitrogen shield) in a turning operation to achieve *in situ* surface hardening of AISI 1018 steel. Preliminary results suggest that the tool–chip interface temperature provides sufficient energy to decompose the feed gas. This enables carbon diffusion into the work surface which, in effect, carburizes the surface and increases the hardness during the turning operation. It is proposed that this approach may enable the machining of low hardness materials, while simultaneously providing increased surface hardness for the machined product. This could result in the reduction/elimination of post-machining heat treatment and could, therefore, have significant implications for the die/mold manufacturing community.

1. Introduction

A common challenge in die/mold machining of stamping dies, forming dies, forging dies, injection molds, and blow molds, for example, is that the hardness of the finished product must be high to achieve long life for the die/mold. This leads to two options: (1) machine the die/mold blank in the hardened state, often referred to as hard machining (turning/milling); or (2) use post-machining heat treatment to realize the required hardness. For the former, tool wear can be a primary limitation to maximized profit. Larger forces with the accompanying vibrations and corresponding degradation in surface finish must also be considered [1]. For the latter, maintaining geometric accuracy of the finished mold can be a challenge and production costs increase due to the additional manufacturing process.

In this work, an initial study regarding the application of a carbonaceous feed gas (acetylene,[1] C_2H_2, with a nitrogen, N_2, shield to minimize oxidation) in a turning operation to achieve *in situ* surface hardening is described. Turning tests were carried out using AISI 1018 steel tube stock, while measuring the spindle power and cutting tool surface. Post-process hardness measurements suggest that the tool–chip interface temperature provided sufficient energy to decompose the feed gas and diffuse the free carbon into the work surface. This carbon diffusion effectively carburized the surface and increased the hardness during the turning operation.

2. Related studies

The use of carbonaceous feed gas in machining is not novel to this work. Casstevens [1] performed diamond turning of steels in a carbon-rich environment by enclosing the work zone in a flexible plastic bag and feeding: (1) carbon dioxide (CO_2) and (2) methane (CH_4) into the enclosure. The purpose of these tests was to reduce the excessive tool wear generally observed when diamond turning steel due to the chemical affinity and high temperatures/pressures between the workpiece and cutting edge [2]. Hitchiner and Wilks [3] also investigated the application of methane to the cutting zone to reduce tool wear in diamond turning. In related work, Shimada et al. proposed the use of a reduced oxygen atmosphere for the diamond turning of copper [4]. A decrease of tool wear to less than a few percent of that measured under the normal conditions was observed.

Carbonaceous gases have also been used to reduce friction and wear at high-temperature interfaces in a more general sense [5–8]. Recently, Argibay et al. demonstrated the ability to provide continuous solid lubrication through vapor phase delivery of carbonaceous gases [9]. Pin-on-disk experiments were performed at 650 °C with a 2 N normal load and 50 mm/s sliding speed; a 20× reduction in the friction coefficient was observed.

Additionally, experiments have been completed to demonstrate the use of process heat to modify a part's surface hardness. Brinksmeier and Brockoff [10] showed that grinding heat can be

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[1] Acetylene was selected for convenience. Other feed gas choices are also available.

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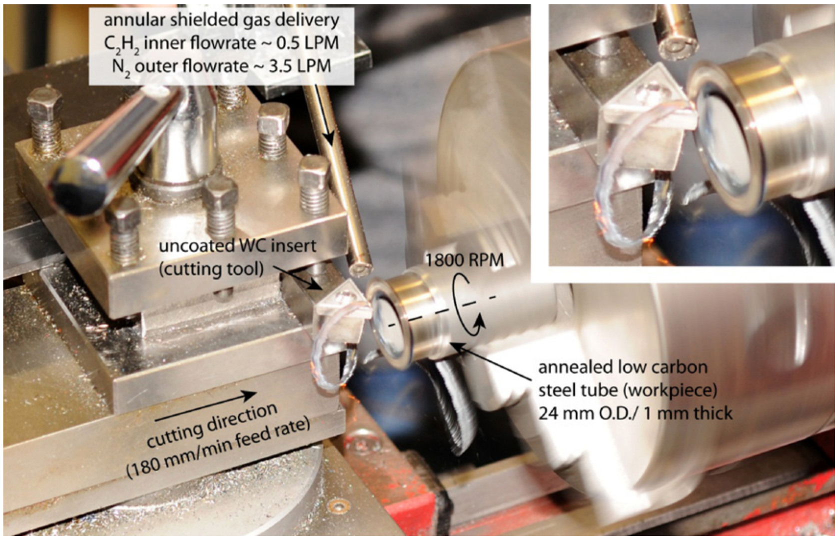

Fig. 1. Experimental setup showing the turning operation. An uncoated, grade C-5 WC insert was used to turn an annealed low carbon steel tube (24 mm diameter with 1 mm wall thickness). The tool feed direction (180 mm/min) and the nitrogen-shielded acetylene gas delivery tubes are also identified. Inset: close-up of the cutting operation.

Fig. 2. Gas delivery system. The inner tube supplied the acetylene gas. The outer annular tube provided the nitrogen gas shield.

used to induce martensitic phase transformations in the surface layer of components. In their “grind-hardening” process, the combination of the high thermal and mechanical loading was shown to produce increased surface hardness. Martensitic layers were observed in hyper- and hypo-eutectoid steels with depths up to 0.25 mm. In related work, Chou used transient thermo-mechanical loading during turning to generate a hardened layer in AISI 4340 steel [11].

3. Test setup

The test setup for the acetylene gas application is shown in Fig. 1. For the cutting tests, orthogonal cutting conditions were approximated by machining the end of a 24 mm outer diameter AISI 1018 steel tube (1 mm wall thickness) using a grade C-5 uncoated tungsten carbide (WC) insert. A spindle speed of 1800 rpm provided a cutting speed of approximately 2.2 m/s for all tests. A nominal feedrate of 180 mm/min was also specified (0.1 mm/rev). In order to encourage exposure of the machined surface to the acetylene gas, an intermittent cutting profile was commanded. In this procedure, the tool was fed into the workpiece at the selected feedrate for 0.1 mm (one revolution), retracted by 1 mm, and then the cycle was repeated for 50 iterations; the total cut length was approximately 5 mm. This provided chip breaking and periodically exposed the cut surface (and tool) to the acetylene gas.

The gas was delivered to the system by the concentric tube assembly shown in Fig. 2. The acetylene flowrate (through the inner tube) was approximately 0.5 liters per minute (LPM) and the nitrogen flowrate (through the outer tube) was approximately 3.5 LPM. The nitrogen shield was included to minimize oxidation. The flow rates were maintained such that the acetylene gas did not ignite during the cutting operation.

In order to monitor the process performance, a digital microscope was used to intermittently capture images of the cutting insert's rake and flank faces (60× magnification) without removing the insert from the tool post. Additionally the spindle power was recorded at sampling rate of 10 kHz during the cutting tests. A new data point was recorded every 0.01 s by averaging the previous 100 samples. Changes in the tool geometry and spindle power were used to monitor tool wear.

4. Experimental results

An example spindle power profile for the intermittent cutting process with the acetylene/nitrogen gas feed is provided in Fig. 3. This represents the cutting process for one workpiece (approximately 5 mm cutting length). The spindle power initially increases when the spindle speed is ramped from 0 to 1800 rpm. It then drops

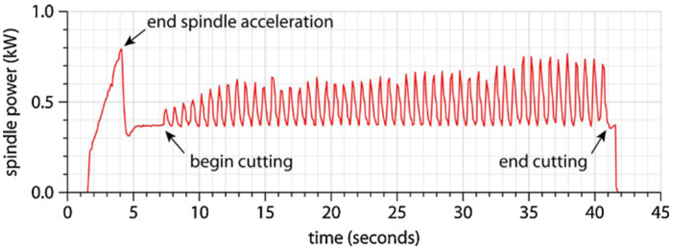

Fig. 3. Spindle power output over the time span of a single run, equivalent to 5 mm of total cutting along the tube length in 0.1 mm cutting intervals with a retraction distance of 1 mm between cuts. The target tool feed rate was 180 mm/min.

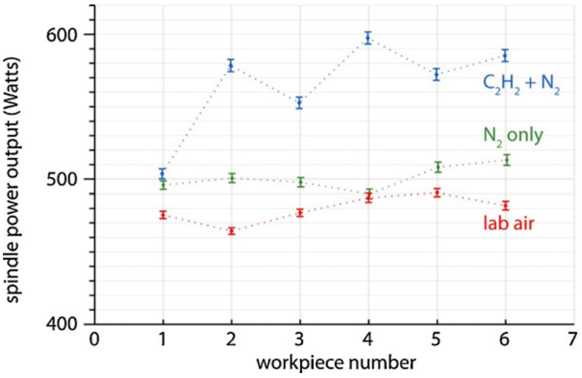

Fig. 4. Spindle power as a function of the number of workpieces (steel tubes). The plot provides a qualitative measure of the progression of tool wear for the three cutting environments using otherwise equivalent cutting conditions. The flowrates of the acetylene and nitrogen were 0.5 LPM and 3.5 LPM, where applicable. The error bars correspond to the mean of the standard deviations for the full data set of each test.

to a value of 375 W before cutting begins. It is observed that the mean power for each cut increased over the length of the test; this indicates that the tool is wearing as the cutting time increases. Tests were also completed with no gas feed and nitrogen gas only. A comparison of the mean spindle power variation with the number of workpieces is displayed in Fig. 4. These results indicate that the introduction of the acetylene gas promotes more rapid tool wear. This result was confirmed by the rake face images (no appreciable flank wear was observed). Fig. 5 shows the insert rake face after three complete workpieces were machined for both the air and acetylene/nitrogen environments. An accelerated wear rate was observed for the feed gas environment.

Due to the increased wear rate, it was inferred that the workpiece surface was hardened by the acetylene gas. Hardness measurements were therefore completed using a nano-indenter with a Berkovich tip after sectioning and polishing a machined tube specimen. Fig. 6 shows an increase in hardness from an average of 3.3 GPa in the bulk material (>40 μm from the machined surface) to 4.3 GPa at the surface for the acetylene/nitrogen gas case; this represents an increase of 30%. No trend in hardness with distance from the machined surface was observed for the lab air cutting tests. Despite the potential limitations imposed by the increased wear rate (appropriate coatings could be used to mitigate this issue, for example), the higher hardness values near the machined surface under the application of the acetylene/nitrogen gas could be exploited to achieve improved mechanical performance.

5. Discussion

While follow-on tests will be required to further explore the use of a carbonaceous feed gas to provide *in situ* hardening of machined surfaces, the initial results show some promise. To further explore the rate of pyrolytic[2] carbon deposition during the cutting process, the process temperature can be approximated using the temperature at the shear plane. It is a common assumption in chip-tool computations that the work material is instantly and uniformly heated to the shear plane temperature as it passes through the shear zone during chip formation [12]. Eq. (1) expresses the shear plane temperature, T_s, as a function of the workpiece-tool combination's specific cutting energy, K_s, the force angle, β, the shear plane angle, ϕ, the specific heat per unit volume for the workpiece material, ρc, and room temperature, T_r. Using approximate values of $K_s = 2100\,\text{N/mm}^2$, $\beta = 17^\circ$, $\phi = 28^\circ$, $\rho c = 3.7\,\text{N/mm}^2\,^\circ\text{C}$, and $T_r = 20\,^\circ\text{C}$, the shear plane temperature is predicted to be 495 °C.

$$T_s = \frac{K_s \cos(\beta + \phi)}{\rho c \cos(\beta)\cos(\phi)} + T_r \tag{1}$$

Depth hardness profiling for a machined tube, as illustrated in Fig. 6, suggests that the process of carburization by chemisorption of pyrolyzed feed gas surface byproducts penetrated less than 20 μm into the workpiece. Noting that the nominal chip thickness was 100 μm, it is arguable that the majority of the enhanced tool wear due to carburization of the near surface occurred in the process of initiating cutting during a cycle (*i.e.*, cutting through the hardened layer). The same effect is observed in milling, where it is generally preferred to use down (climb) milling conditions when machining materials that exhibit significant work hardening. The thicker chip at the cut entrance for down milling enables the tool to cut "under" the work hardened layer. The opposite is true for up (conventional) milling, where the initially thin chip causes shearing of the work hardened layer. Indeed, though not shown in this manuscript, the authors observed no apparent change in tool wear or spindle power in the presence of acetylene feed gas during uninterrupted tube cutting with otherwise equivalent conditions. The process of surface hardening also likely occurs in this uninterrupted cutting, though without any adverse effect on tool wear as the tool is continuously immersed in the workpiece (below the surface hardened layer).

Neglecting acceleration and controller command/reaction times, the portion of cycle time spent cutting for a 0.1 mm/rev feed rate was approximately 0.03 s. The portion of cycle time spent moving the tool to its stand-off position and returning to the workpiece surface for the next cutting cycle was approximately 0.7 s. This retraction/approach time interval was then the surface exposure time to acetylene. The pyrolytic decomposition of acetylene results in the formation of a carbon film composed of the various allotropes of carbon (amorphous, sp^2, and sp^3) [13]; the density ratio of acetylene and solid carbon is approximately 1:2000. For an acetylene flow rate of 0.5 L/min, assuming that: (1) the gas has expanded to room temperature and pressure after exiting the nozzle; and (2) all the acetylene is pyrolytically decomposed to solid carbon and hydrogen gas, it would take only ∼25 μs to deposit a single monolayer thick film of carbon on the exposed end of the steel tube (∼75 mm^2 in cross-sectional area). Although this is a crude approximation that assumes ideal and complete deposition and neglects several complexities affecting the deposition process, it is meant as an order of magnitude comparison suggesting that, even at a relatively low flow rate, there is likely ample time and available carbon to generate thick pyrolytic carbon films on the surface of the workpiece on the time scales of a machining operation.

The depth of carbon penetration into the workpiece is a result of solid interdiffusion, a temperature-activated process exhibiting Arrhenius behavior. For one-dimensional diffusion, Fick's second law of diffusion simplifies to the linear diffusion equation (Eq. (2)), expressing the time rate of change of carbon concentration, c, as a function of depth, x, as proportional to a diffusion coefficient, D (units of cm^2/s).

$$\frac{dc(x,t)}{dt} = D(T)\frac{d^2c(x,t)}{dx^2} \tag{2}$$

The diffusion coefficient is modeled as a function of absolute temperature, T (in K), the ideal gas constant, R, an activation energy, E_a, and a system-characteristic diffusivity constant, D_o, (in cm^2/s). See Eq. (3).

$$D(T) = D_o \exp\left(-\frac{E_a}{RT}\right) \tag{3}$$

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[2] Pyrolysis generally describes the decomposition or transformation of a compound due to the addition of heat in the absence of oxygen.

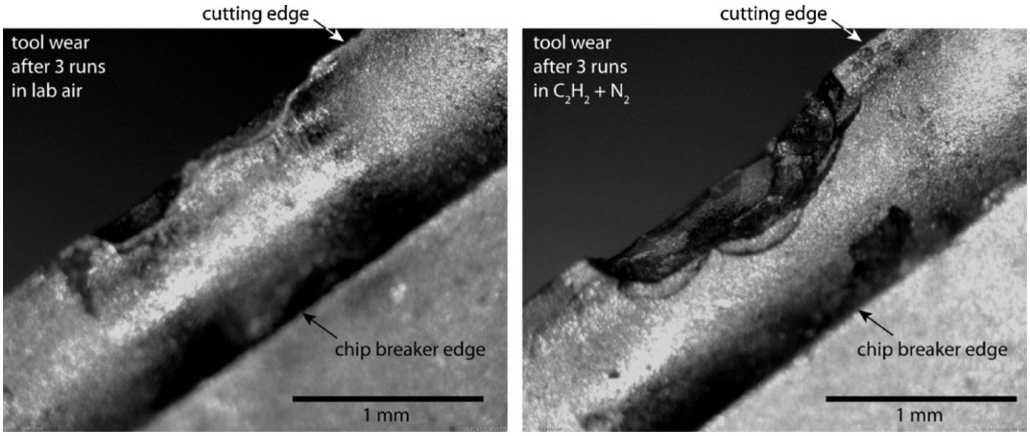

Fig. 5. Representative optical images showing damage on the tool cutting edge after three workpieces in lab air (left image) and in nitrogen-shielded acetylene (right image). Tool damage was greater when machining was performed in the hydrocarbon environment.

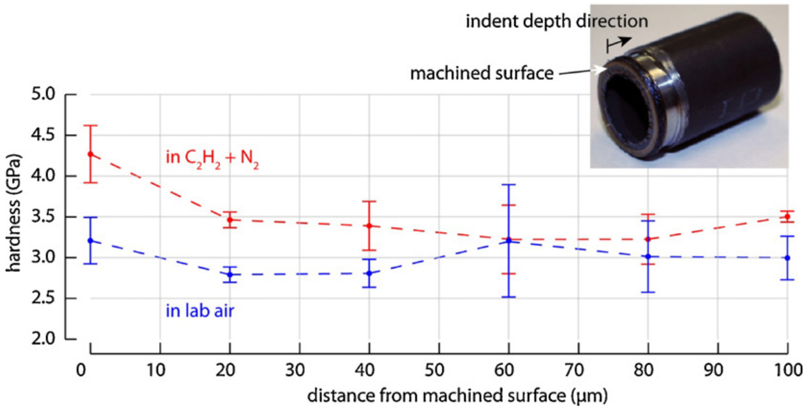

Fig. 6. Plot of hardness as a function of distance from the machined steel tube surface (into the bulk). Hardness measurements were performed using a nano-indenter with a Berkovich tip. The data points and error bars represent the mean and standard deviation of three repeated measurements at each indentation depth.

Wells and Mehl [14] measured the diffusivity of carbon in austenitic steel and developed the function shown in Eq. (4) where the diffusivity coefficient, D_C^Y, is a function of carbon concentration, C (in weight percent), and temperature.

$$D_C^Y(C,T) = (0.07 + 0.06C)\exp\left(-\frac{3.2\times 10^4}{RT}\right)\ \mathrm{cm^2/s} \qquad (4)$$

A first-order approximation of the carbon concentration profile with depth into the workpiece as a result of exposure to acetylene may be calculated by solving Eq. (2) while treating the workpiece as a semi-infinite medium. Following the solution presented by Glicksman [15], the Laplace transform method was used to reduce Eq. (2) into a linear ordinary differential equation. This resulted in a time-dependent expression of carbon concentration (normalized to the surface concentration, C_o) as a function of depth into the workpiece, x, and time; see Eq. (5).

$$\frac{C(x,t)}{C_o} = erfc\left(\frac{x}{2\sqrt{Dt}}\right) \qquad (5)$$

A plot of the normalized concentration profile after an elapsed time equal to the approximate exposure time of the workpiece during intermittent cutting (0.7 s, as illustrated in Fig. 3) is provided in Fig. 7. A constant, homogeneous temperature near the surface of the workpiece equal to the calculated shear plane temperature (~500 ± 100 °C) was assumed.

Although a direct correlation between hardness and diffused carbon is confounded by numerous complexities, there are examples of low temperature (on the order of 400 °C) carbon diffusion treatments as a means of case hardening steels [16,17]. The first-order approximation of carbon penetration depth shows that it is possible to diffuse significant amounts of carbon into the workpiece over fractions of a second at temperatures commensurate

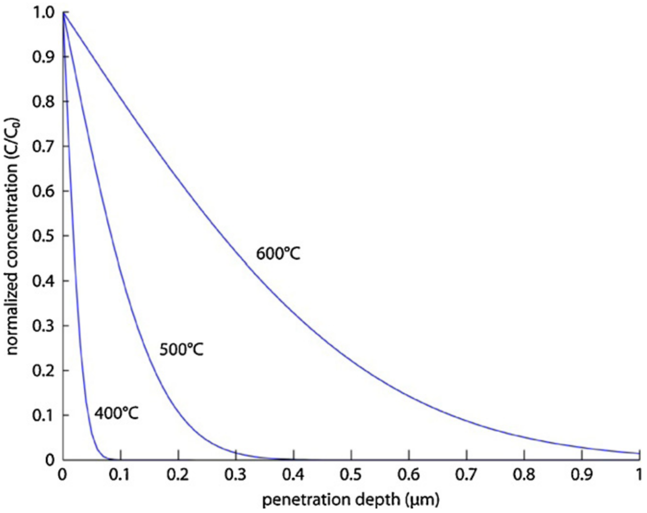

Fig. 7. The normalized near-surface carbon concentration profile after 0.7 s was calculated assuming one-dimensional diffusion into a semi-infinite solid at a near-surface homogeneous temperature equal to the calculated shear plane temperature for the cutting operation (~500 ± 100 °C). A penetration depth of zero corresponds to the workpiece surface.

with dry cutting of steel, generating a carbon-rich film on the order of hundreds of nanometers to micrometers thick, depending on the surface concentration of carbon. These calculations, along with depth profiles of hardness and a clear increase in tool wear with exposure to low flow rates of shielded acetylene gas, indicate that a hardened surface film was developed on or beneath the surface of the steel workpiece. It may therefore be possible to case harden a steel workpiece after a machining operation by simply exposing the workpiece to a low flow of shielded acetylene gas immediately after cutting.

6. Summary

This paper described initial tests regarding the application of acetylene feed gas (with a nitrogen shield) to increase surface hardness during intermittent turning of AISI 1018 steel. An increase in surface hardness of 30% was observed with a penetration depth of not more than 20 μm. Tool wear was also monitored for the uncoated tungsten carbide insert. It was found that the application of the carbonaceous feed gas tended to accelerate the wear rate; this effect could be addressed using appropriate tool coatings. However, if surface hardening of a machined steel component is desired, then acetylene (or a similar carbonaceous feed gas) may be used to achieve *in situ* vapor phase carburization.

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