A simple technique to characterize the role of work hardness in hard part machining

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Abstract: An experimental technique that employs a Jominy end quench test specimen for rapid characterization of the machining response of a steel with reference to its bulk hardness is presented. Employed widely by metallurgists to appraise the hardenability of a steel, the Jominy test entails the quenching of a standard cylindrical specimen from one end, on having heated it to the austenitizing temperature. The cooling rate at any transverse section of the specimen is therefore dependent on the distance of the section from the quenched end, which brings about a continuous variation of material hardness along its length. The use of such a specimen as the workpiece to investigate the machining response of the steel with respect to its hardness significantly reduces the time, effort and cost involved in reliably optimizing a hard part machining application. Cutting force and surface finish data are presented to demonstrate this simple, innovative concept.

Keywords: cutting forces, hard cutting, Jominy end quench test, surface finish

1 INTRODUCTION

Machining of hard steels by cutting has continually evolved in the past and has of late matured into an established technology owing to the emergence of advanced tool materials. Process attributes such as higher material removal rates, increased flexibility and environmental benefits associated with the prospect of dry machining have enabled hard part cutting seize numerous applications that have traditionally belonged to the domain of grinding processes.

By virtue of its influence on the mechanism of chip formation, the work material hardness has a critical influence on machining responses such as cutting forces, tool life and surface integrity. Accordingly, the role of work hardness has been the focus of several investigations on machining, especially in the context of hard part cutting.

During the course of an investigation on machining AISI 4340 steel, Matsumoto *et al.* [**1**] observed that the shear plane angle increased linearly with an increase in work hardness in the range of 25–50 HRC, signifying a decrease in the cutting strain. Furthermore, they detected a transition in the mechanism of chip formation from one that generates continuous chips to one that forms segmental chips at a hardness of about 50 HRC. This is in concurrence with the report of Komanduri *et al.* [**2**] that the incidence of catastrophic shear instability in the primary shear deformation zone is influenced by the work hardness. Their experiments on high-speed machining of the steel above further indicated that the cutting speeds at which the instability was fully developed increased with a decrease in hardness.

An interesting feature associated with the machining of steels is that the cutting force characteristics exhibit distinct minima with respect to work hardness, as observed by Wu and Matsumoto [**3**] in the case of AISI 4340 steel. Ng and Aspinwall [**4**] have reported similar cutting force-hardness characteristics for AISI H13 tool steel. These experiments related to turning operations and the minimum cutting force was found to occur around a hardness of 40 HRC.

Liu *et al.* [**5**] used a tool-work thermocouple technique to observe that the cutting temperature exhibited maxima around a work hardness of about 50 HRC, for a wide range of cutting conditions when turning AISI 52100 bearing steel using polycrystalline cubic boron nitride (PCBN) tools. Matsumoto and Hsu [**6**] also found that the peak workpiece temperature increased with hardness up to 50 HRC when machining AISI 4340 steel. They further noticed that the cutting heat was transferred to a greater depth beneath the machined surface for a harder steel, despite the fact

The MS was received on 6 May 2003 and was accepted after revision for publication on 4 July 2003.

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that a larger shear angle would in fact reduce the heat apportioned to the workpiece.

In the light of the aforementioned effects of work hardness on cutting forces and temperatures, it can be expected that the hardness would exert a significant influence on the integrity of the machined surface. Matsumoto *et al.* [**1**] noted that the work hardness affects both the distribution and the magnitude of the residual stresses on the generated surface/subsurface, and that the residual stresses shift from being tensile to compressive with an increase in hardness. Subsequently, Wu and Matsumoto [**3**] explained this phenomenon with reference to the orientation of the primary shear deformation zone, based on an assertion that mechanical loads predominate thermal effects in the development of residual stresses.

On investigating the role of hardness on the roughness of the surface generated, Hassan and Hayajneh [**7**] found that the surface finish improved with increasing hardness when turning AISI 1060 medium carbon steel in the range of work hardness from 165 to 250 HB. The interaction effect of hardness with both the feed rate and the cutting speed was also reported by them to be statistically significant. Oishi [**8**] presented interesting results on the prospect of obtaining mirror-like surfaces when machining steel, with reference to built-up edge phenomenon that generally limits the achievable finish. He showed that the formation of a built-up edge could be eliminated even under cutting conditions that are most favourable to its formation, provided the work hardness is above a certain critical value, thereby facilitating the generation of ultra-smooth surfaces.

Tool life is another machining response that is notably affected by work hardness. Liu *et al.* [**5**] observed the life of PCBN tools to exhibit a minimum at a hardness of 50 HRC, which corresponded to the maximum cutting temperature when machining AISI 52100 steel. Poulachon *et al.* [**9**] investigated the effect of work hardness on the performance of PCBN tools when machining AISI 52100 steel over a hardness range of 38–60 HRC and found that the cutting speed and workpiece hardness interacted to influence the chip formation mechanism, with the cutting temperature being the link between the two factors. Modelling the tool life using an extended Taylor's model showed the workpiece hardness to have a significant effect on the life of PCBN tools, on the same order as that of cutting speed.

Hard steel components are generally employed in high-performance applications, wherein the functional behaviour of a component is decisively influenced by the response of the material to machining. It is therefore imperative that product designs be conceived with a systems approach, considering machining attributes in addition to strength requirements, particularly for batch- and mass-produced components. With reference to the foregoing discussion that highlights the critical influence of work hardness on key issues such as surface finish, cutting forces and tool life, it is essential that the work hardness be taken into account for optimizing a hard part component/machining application. Of particular significance is the identification of the hardness level for a certain steel that corresponds to the transition from continuous to segmental chips [**1**, **2**] in terms of machining-induced part distortion and vibration issues, and the critical hardness above which the built-up edge is excluded [**8**] in the interest of attainable surface finish. The hardness values at which these transitions materialize for a particular steel would depend on the cutting conditions, and for want of theoretical models with predictive capabilities, it is expedient to resort to experimental characterization.

The methodology generally employed to characterize the machining performance of a steel with respect to its hardness [**1**–**9**] is to perform cutting tests on different blocks of material samples that have been subjected to varied heat treatment cycles in order to obtain the desired hardness levels. This approach provides limited resolution in terms of hardness values on account of the sample preparation phase being rather effort intensive, more so if many different steels are being considered. This is indeed a severe shortcoming if the objective is to detect transitions in machining performance. The variability in hardness within a sample block of material is also a problem.

To this end, a simple experimental technique that employs a Jominy end quench test specimen for rapid characterization of the machining response of a steel with reference to its hardness is presented in this paper. This technique significantly reduces the time, effort and cost involved in reliably optimizing a hard part machining application. Following on a brief description of the technique, cutting force and surface finish data are presented to demonstrate this simple, innovative concept.

2 JOMINY END QUENCH TEST

The Jominy end quench test [**10**] is widely used by metallurgists to characterize the hardenability of a steel that refers to the capacity of a steel to transform from austenite to some fraction of martensite at a given depth when quenched under a given condition. The test comprises a standard specimen (of length 100 mm and diameter 25 mm) of the steel that is heated uniformly to the austenitizing temperature, which is subsequently quenched selectively from one end (see Fig. 1) by a jet of a quenchant, under-controlled conditions. The specimen is thus subject to continuously varying cooling rates along its length, ranging from a very rapid rate at the quenched end to air-cooling at the other, which gives rise to a continuous decrease in hardness with distance from the quenched end.

For a set of cutting conditions, the use of such a specimen as the workpiece would provide cutting force

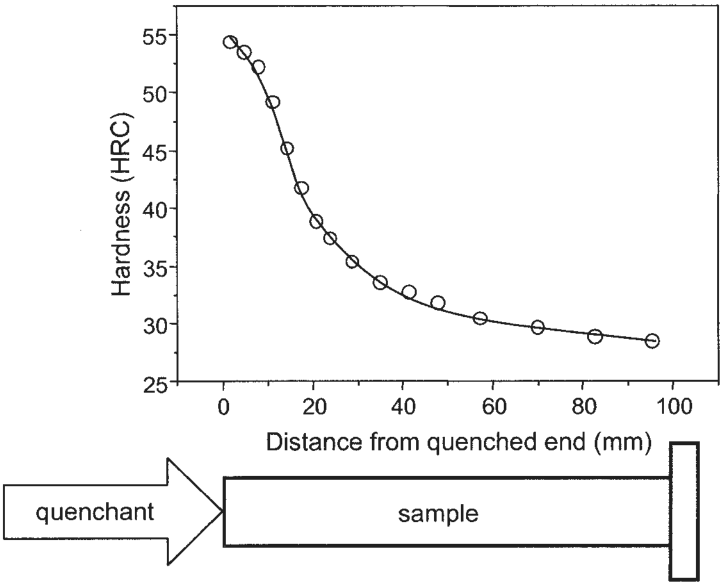

Fig. 1 Schematic representation of the Jominy end quench test, and a typical hardness profile obtained for AISI 4140 steel with water quench

and surface finish data as a function of hardness in a single pass. For the corresponding conditions, it is thus possible to identify the hardness that corresponds to the minimum cutting force. The critical hardness above which the steel entails material removal free of the built-up edge phenomenon, leading to a good surface finish, can also be identified with ease. Furthermore, data acquired thus would be invaluable for calibrating and validating mechanistic cutting force models.

3 EXPERIMENTAL RESULTS

Experiments to demonstrate the novel concept were conducted on AISI 4140 steel. After the end quenching operation with water, the hardness obtained on the specimen varied from 28 to 55 HRC along its length (Fig. 1). Experimental conditions and the results obtained are detailed below.

The cutting force-hardness characteristic was obtained in a face milling operation (Fig. 2), using a cutter with axial and radial rake angles of · 6°, utilizing just one insert (TiN-coated, RNMN32) to circumvent problems with runout. A cutting speed of 150 m/min, an axial depth of cut of 0.2 mm, a width of cut of 18 mm and a feed/tooth of 0.05 mm were employed, using down-milling with no cutting fluid. The three components of cutting force were measured using a Kistler platform dynamometer. To account for the effect of flank wear on cutting forces, forces were measured for passes proceeding from hard to soft and vice versa, using inserts with identical levels (~60 μm) of flank wear. The incremental wear after each of these two passes was measured to be similar (~15 μm). The resultant peak cutting force shown in Fig. 2 as a function of hardness indicates that for this steel and the set of cutting conditions used, the force characteristic exhibits a minimum around 32 HRC, and that the force increases somewhat linearly with hardness thereafter.

The decrease in cutting force with increasing hardness (to the left of the minimum) is explained [**11**] with reference to effects associated with cutting temperature and chip–tool contact length. With an increase in hardness, the cutting temperature increases, leading to thermal softening of the steel. In addition, the increase in shear angle associated with increasing hardness [**1**] leads to a decrease in the chip thickness, which in turn results in a

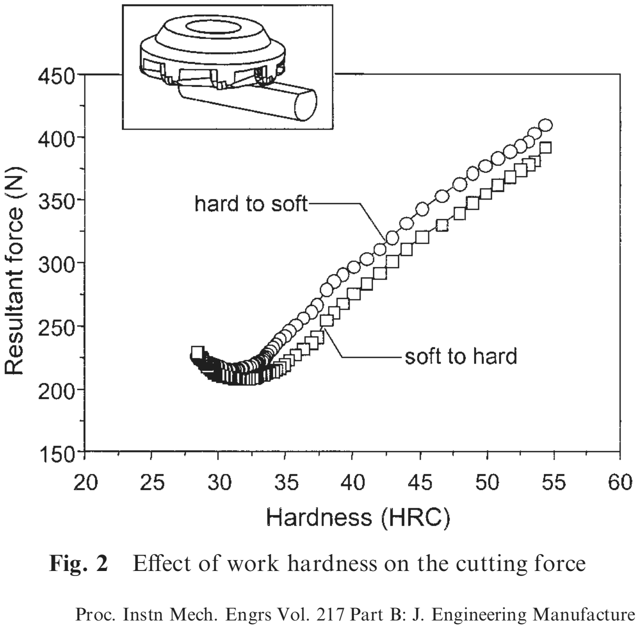

Fig. 2 Effect of work hardness on the cutting force

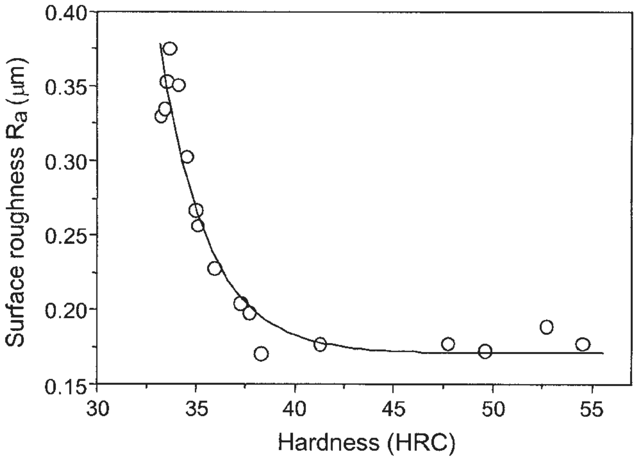

Fig. 3 Effect of work hardness on the roughness of the generated surface

decreased tool–chip contact length. Both of these factors promote a decrease in cutting forces. In this regime the energy associated with chip formation is related to the flow strength of the material. Once the cutting forces reach a minimum with respect to hardness, a further increase in temperature is not commensurate with the increase in hardness, on account of the deformation energy associated with cutting the hard/brittle steel being relatively lower. This diminishes the material softening effect, resulting in an increase in the cutting forces.

The effect of work hardness on the roughness of the surface generated was studied in a turning process performed dry, with a tool of back rake angle of · 5°, an inclination angle of · 9° and a side cutting edge angle of 62.5°. The insert (TiN-coated, DNMG) had a nose radius of 0.8 mm. The cutting conditions employed were a cutting speed of 150 m/min, a feed rate of 0.05 mm/rev and a depth of cut of 0.2 mm. The roughness was characterized in terms of the parameter R_a and the measurements conformed to an evaluation length of 4 mm and a cut-off length of 0.8 mm. The data shown in Fig. 3 (representing an average of four measurements at each section) indicate that the roughness is critically affected by the work hardness. For this material and the set of machining conditions above, the roughness increases considerably for hardness values lower than about 40 HRC. In this case, it is interesting to note that to obtain a fine finish, it would suffice to heat-treat the material to a hardness of ~45 HRC, rather than, say, 55 HRC, which would be more difficult to machine. Examination of the surface pointed to the built-up edge phenomenon being responsible for such deterioration in the finish with a decrease in hardness, as proposed by Oishi [**8**].

This short communication pertains to the presentation of the proposed novel experimental technique, without delving into detailed explanations for the observed phenomena. Experiments using this technique to comprehend the physics behind the effect of work hardness on the mechanism of material removal, cutting forces and surface finish are currently in progress, the results of which will be reported in due course.

4 CONCLUSIONS

This paper presents a simple, innovative experimental technique for the rapid characterization of the machining response of a steel with respect to its hardness. The technique can be adapted for various machining processes. For a particular steel and a set of cutting conditions, using this technique it is possible to identify the hardness that corresponds to the minimum cutting force and the hardness below which the built-up edge phenomenon compromises the finish of the generated surface, in just a single pass. The technique can also be employed for the swift calibration and validation of mechanistic machining models. With respect to optimizing a hard part machining application in terms of work hardness, the proposed technique represents a substantial saving in time, cost and effort, over the conventional procedure of conducting experiments on different blocks of work material samples that have been subjected to various heat treatment cycles.

ACKNOWLEDGEMENT

The authors acknowledge the financial support from AUTO21, a national research initiative supported by the Government of Canada through the Networks of Centers of Excellence, for the project entitled 'High Speed Machining of Dies and Molds'.

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