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Effect of grinding-induced cyclic heating on the hardened layer generation in the plunge grinding of a cylindrical component

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ABSTRACT

This paper discusses the effects of the grinding-induced cyclic heating on the properties of the hardened layer in a plunge cylindrical grinding process on the high strength steel EN26. It was found that a multi-pass grinding brings about a uniform and continuous hardened layer along the circumference of the cylindrical workpiece. An increase of the number of grinding passes, leads to a thicker layer of hardening, a larger compressive residual stress and a deeper plastic deformation zone. Within the plastic deformation zone, the martensitic grains are refined by the thermo-mechanical loading, giving rise to a hardness of 12.5% higher than that from a conventional martensitic transformation. The coupled effects of heat accumulation and wheel wear in the multi-pass grinding are the main causes for the thickening of the hardened layer. A too small infeed per workpiece revolution would result in insufficient grinding heat, and in turn, bring about an undesirable tempered hardened layer and a reduction of its hardness.

Introduction

It is known that the external stresses applied on a material undergoing phase transformation can bring about a favourable microstructure of the hardened material [1–3]. However, it is practically difficult to apply complex stresses to a selective area in a heating/cooling cycle. Grinding-hardening, a thermo-mechanical technique that uses the stress-induced heat in grinding, is suitable for this purpose [4–7]. A wear test on the grinding-hardened layer on an AISI 4140 steel has shown that the wear resistance can be two orders higher than that of a conventional heat-treated sample [8]. Besides, the tensile residual stresses, which are prevail in quenched steel [9] and are detrimental to the fatigue strength, can be suppressed by grinding-hardening [10]. However, grinding configurations play important roles in determining the trajectories of grinding-induced heat sources, and thus in the profile generation of hardened layers. In a surface grinding, the heat source moves along a linear feeding direction [6,11]; whereas in a cylindrical grinding configuration, the trajectory of the grinding-induced heat source is the result of both axial and rotational motions [12,13], making the prediction and control of the hardened layer more difficult. For example, in a traverse cylindrical grinding, due to the overlapping of the sequential grinding passes, the hardened layer was found to be non-uniform along the axial direction of the cylinder [14]. In plunge grinding, however, it was reported that the way of the wheel-work engagement could largely influence the circumferential uniformity/continuity of the hardened layer [12,13,15]. The main cause of this non-uniformity is the varying depth of cut, $a(\theta)$, during the wheel engaging and retracting in a spiral plunge (Fig. 1a), which alters the heat source intensity and thus the hardened layer thickness. To improve the situation, a radial plunging method [12] was proposed as illustrated in Fig. 1b, where the grinding wheel first plunged into the workpiece at the full depth of cut when the workpiece was stationary and then the workpiece started to rotate to realise a material removal in a single workpiece revolution under a constant full depth of cut. In this way, however, the heat input at the exit point of the wheel-workpiece engagement would be low, which eventually gave rise to a non-hardened surface area. Another attempt [15] was later on proposed to use a volume of sacrificial material at the engage point, as illustrated in Fig. 1c, to enable an extra grinding-heating induced by a greater material removal. However, at the wheel exit point, the grinding-heating led to the tempering of the hardened layer, making its hardness decreased.

An interesting investigation on surface grinding [10] showed that a multi-pass grinding may provide a solution to the above problem. Based on this, a plunge grinding of a cylinder can also be performed in the way of multi-passes, i.e., by completing the grinding of a specified total depth of cut in multiple revolutions of the workpiece to produce a thicker and a more uniform hardened layer. Nevertheless, such a multi-pass approach makes a workpiece experience a cyclic surface heating and cooling, and thus a

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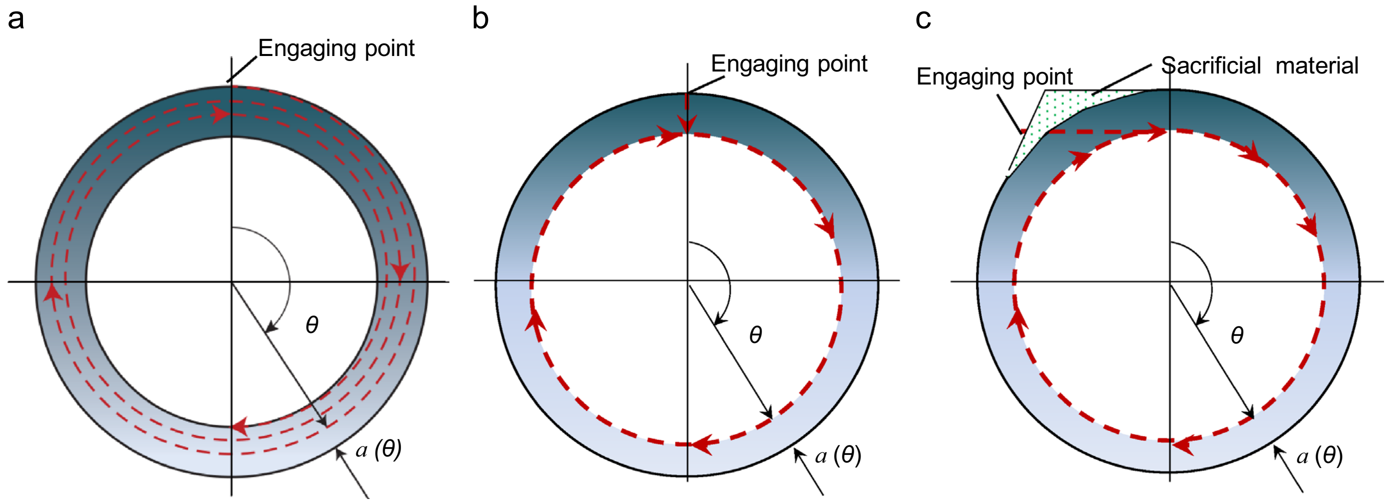

Fig. 1. Schematics of plunge grinding strategies. (a) Spiral grinding; (b) radial grinding; and (c) tangential grinding.

more complex mechanism of microstructural changes in the workpiece material associated with, e.g., heat accumulation and grindability of the hardened layer created from previous cycles. Moreover, grinding heat and stresses cause subsurface deformation of the workpiece, which in turn, alters the properties of the hardened layer. However, no understanding is available about the effect of multi-pass grinding heating on a cylindrical workpiece.

This study aims to understand the feasibility of the multi-pass grinding to obtain a uniform hardened layer on a cylindrical component. The assessment will be made through a systematic grinding experiment under various grinding conditions. The results obtained, including the geometry of the hardened layer and the microstructure and its effect on hardness and residual stresses, will be analysed with the heat transfer mechanisms and wheel surface conditions.

Experiment

The grinding experiments were conducted on a compact CNC cylindrical grinder, GRN-20 Shigiya. A vitrified-alumina grinding wheel, 57A90SV, of 300 mm in diameter and 25 mm in width was selected. The wheel's low thermal conductivity allows a high percentage of the grinding heat to conduct into the workpiece [16]. As the abrasive grain hardness decreases with the increase of temperature [17], the hardness grade *S*, which is higher than that in a normal grinding condition, was selected in grinding-hardening. Another reason is that the grinding heating, which is essential in the hardening-grinding, is minimised in a low-grade grinding wheel. This is because its low hardness facilitates the grain fractures, which allows new and sharp grinding grains continuously formed on the wheel surface without significant chip loadings. The up-grinding mode was used, with the wheel speed of 2080 rpm, i.e., a linear speed of 65.34 m/s. Prior to each test, the wheel was dressed using a multi-point diamond dresser of 10 mm in diameter, with the traverse speed of 206 mm/min and dressing rate of 25 μm/pass. The total dressing depth was above 100 μm to ensure that fractured wheel bonding was completely removed. The workpiece material was the BS970-EN26, a 2.5% Ni–Cr–Mo high tensile steel (please see the material composition in Table 1), which is characterised by its high hardenability and high tensile strength (1000–1150 MPa). The hardness of the as-received En26 is around 300 HV, which could be increased to more than 650 HV by quenching at temperatures at 820–850 °C [18]. The diameter of workpiece is 50 mm in diameter and 50 mm in length. The details

Table 1
Grinding conditions.

Wheel material/grade	Alumina/57A90SV
Wheel diameter (mm)/width (mm)	300/25
Wheel speed (rpm)/(m/s)	2080/65.34
Dresser material/diameter (mm)	Diamond/10
Dressing method	Multiple point
Dressing steps	Traverse feed: 206 mm/min; dressing rate: 25 μm/pass; total dressing depth > 100 μm;
Workpiece material	BS970-EN26 Steel
Workpiece (EN 26) composition [18]	C:0.4%; Si:0.25%; Mn:0.6%; Ni:2.5%; Cr:0.65%; Mo:0.55%; S:0.025%; P:0.025%
Workpiece diameter/length (mm)	50/50

of the grinding conditions and the composition of workpiece material are shown in Table 1.

Table 2 lists the grinding parameters, where a constant instant infeed per workpiece revolution (d_r=30 μm/rev) was applied, determined by the feed rate v_r and the rotational speed of the workpiece ω_w. The workpieces were ground to different total depth of cut, *f*, which gives rise to a different number of grinding passes *N* ($N = f/d_r$) ranging from 3.5 to 17.5 revolutions. To ensure the roundness of a workpiece ground, a sparking-out of about 5 revolutions was allowed after reaching to the total depth of cut. The grinding-hardening and the subsequent spark-out were completed in one operation without re-dressing the wheel. This is because the diameter variation in a high-infeed grinding is minimal in the low-infeed (30 μm) multi-pass grinding. Thus, the final

Table 2
Grinding parameters.

Machining input			***Nominal parameters***	
Work speed, ω_w (rpm)	Feed rate, v_r (mm/min)	Total depth of cut, *f* (μm)	Infeed per cycle[a], d_r (μm/rev)	No. of grinding revolutions[b], *N* (rev)
20	0.6	105	30	3.5
20	0.6	195	30	6.5
20	0.6	255	30	8.5
20	0.6	315	30	10.5
20	0.6	525	30	17.5

[a] $d_r = \frac{v_r}{\omega_w}$.

[b] Without the spark-out, $N = \frac{f}{d_r}$.