International Journal of Machine Tools & Manufacture 88 (2015) 24–33

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

journal homepage: www.elsevier.com/locate/ijmactool

Hardness control of grind-hardening and finishing grinding by means of area-based specific energy

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ARTICLE INFO

Article history:
Received 11 April 2014
Received in revised form
1 September 2014
Accepted 3 September 2014
Available online 16 September 2014

Keywords:
Grind-hardening
Area based specific energy
Hardness penetration depth
Surface layer softening

ABSTRACT

The grind-hardening process uses the heat generated within the grinding zone in order to produce surface hardening of the workpiece. However, after the process, workpieces present dimensional inaccuracies and poor surface roughness. Thus, a final grinding operation has to be performed. For an industrial implementation of the whole process, two problems need to be solved. On the one hand, on-line control of the hardness penetration depth (HPD) should be achieved. On the other hand, excessive softening of the workpiece has to be avoided during the finishing grinding. This paper, firstly, investigates the feasibility of using the area based grinding energy (E_c'') for the prediction of the HPD. Surface grind-hardening tests carried out on 100Cr6, 42CrMo4 and AISI 1045 steels have shown that, for all the tested parameter sets, a linear correlation exists between E_c'' and HPD. Furthermore, the slope of this linear relationship can be estimated from the chemical composition of the hardened steel based on the equivalent carbon number. On the other hand, the influence of varying wheel dressing conditions on the E_c''–HPD relationship is analysed. Secondly, it has been found that a relationship exists between E_c'' and the surface softening during the finishing grinding operation. This relationship is independent of the grinding parameter combination when the maximum undeformed chip thickness is over a threshold value. Thus, E_c'' is a very appropriate parameter to control both the hardening and the finishing process of grind-hardened workpieces.

1. Introduction

1.1. Motivation

In industry, machine steel components working under high loads and frequent sliding contact have to be subjected to a surface strengthening heat treatment. This process improves fatigue strength and wear resistance while maintaining the toughness of the workpiece. In order to achieve such requirements, an ineffective manufacturing process is usually followed. After soft machining, workpieces have to be cleaned and transported to the heat treatment facility where a thermal or a thermo-mechanical process, *e.g.* case hardening or induction hardening, is applied. Then, workpieces are discharged and brought back to the production line for a final finishing operation that gives them accuracy and a good surface finish. However, this process cannot simply be introduced into the production line, which leads to high costs and longer production times. Moreover, it involves serious health problems associated with the use of toxic coolants [1].

Abrasive machining processes with undefined cutting edges, such as grinding, require a high energy input. In fact, almost all the mechanical energy from the grinding wheel is transformed into heat within the grinding zone, causing the wheel and workpiece temperatures to rise.

Grind-hardening is an innovative technology that uses the heat generated within the contact area so as to achieve surface hardening. In order to do so, during the grinding pass, a short time austenitization is enabled in the surface layer of the machined workpiece [2]. Subsequently, self-quenching effect and the usage of coolant induces a martensitic phase transformation of the generated austenite and the desired hardened layer is obtained [2,3]. This technology can be fully integrated into the production line, and therefore, it offers an outstanding potential to reduce costs, energy and time.

At first, the viability of the process was questioned due to various issues such as the control of the sparks generated, low repeatability of the process [2], or the workpiece geometry. In recent years, this process has been subject of several investigations that have proven its feasibility for surface grinding [2,4–6] and cylindrical grinding [3,7–9].

Abbreviations: CE, Equivalent carbon content; HPD, Hardness penetration depth
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http://dx.doi.org/10.1016/j.ijmachtools.2014.09.001

Nomenclature

a_e	depth of cut, m
b_s	wheel width of cut, m
d_s	wheel diameter, m
e_c	specific grinding energy, J/m^3
E''_c	area specific grinding energy, J/m^2
F_t	tangential force, N
$h_{cu,max}$	Maximum undeformed chip thickness, m
l_c	Wheel-workpiece length of contact, m
P''_c	area specific grinding power, W/m^2
P_c	grinding power, W
T	temperature, K or °C
U_d	dressing overlap ratio
v_f	axial feed rate, m/s
v_s	grinding wheel speed, m/s

Nevertheless, to introduce the process into industry, there are still some issues that must be solved. On the one hand, a closed loop control of the hardness penetration depth (HPD) has to be developed based on on-line measured parameters [9]. On the other hand, after the grind-hardening process, workpieces present important distortions [4] and an inappropriate surface roughness [10]. Thus, a final grinding operation has to be performed. During this operation, workpiece softening has to be controlled. The scope of this paper is to study the feasibility of using E''_c as an in-process control parameter for both grind-hardening and final grinding steps.

1.2. State of the art

1.2.1. Prediction of the hardening depth during grind-hardening

The main difficulty of the use of grind-hardening is the selection of the process parameters, so as to achieve the desired HPD. Many studies have focused their work on studying the maximum performance of the process based on the variation of the wheel characteristics or process parameter combination [2,11–14].

Corundum wheels have a higher thermal resistance compared to CBN grinding wheels. Therefore, if HPD is to be maximised, corundum grinding wheels should be preferred [2]. However, both types of grinding wheels have been used in previous works [2,5–9,13]. A study carried out by Salonitis et al. [14] also concluded that coarser abrasive grains, and an open structure are more appropriated to produce a deeper HPD.

Furthermore, the bond of the wheel can also influence decisively on the heat dissipation of the grinding process. Whereas vitrified bonded wheels should be preferred due to their worse heat conductivity, several experimental tests have shown that resin bonded wheels lead to a slightly higher HPD [2]. However, many authors have successfully used vitrified wheels to carry out grind-hardening operations [4,7–9]. The influence of the grinding wheel dressing parameters on the obtained HPD has not been studied yet.

Regarding the experimental approaches, a thorough investigation was presented by Brockoff, concluding that hardened depths up to 1.8 mm could be obtained with compressive residual stresses in the workpiece surface [2]. Furthermore, it was shown that when feed speed was kept constant, HPD increased with increasing depth of cut. However, when the depth of cut was kept constant, it was observed that HPD increased with decreasing feed speed until a threshold value. Below this threshold feed speed, some phenomenon appeared and HPD decreased. The same effect can be observed in other works [9,10]. However, the explanation of this phenomenon has not been sufficiently discussed.

In order to support the selection of grinding parameters, analytical and numerical models of the grind-hardening process have been developed [3–5,13,15]. Unfortunately, these models are difficult to integrate in an on-line control of the process.

In a previous study [16], it was reported that during cylindrical grind-hardening the HPD can be estimated on-line from the area-based specific energy E''_c. This parameter takes into account, not only the grinding power, but also the wheel-workpiece contact time. The value of E''_c can be estimated from Eq. (1).

$$E''_c = P''_c \cdot \Delta t = \frac{F_t \cdot v_s}{b_s \cdot v_f} \tag{1}$$

where P''_c is the area based grinding power, Δt is the contact time, F_t is the tangential grinding force, v_s is the wheel speed, b_s is the grinding wheel width and v_f is the feed speed.

It was found that a linear correlation exists between E''_c and the HPD for cylindrical grind-hardening. Furthermore, the results suggested that this relationship is constant for different combinations of depth of cut and workpiece speed when wheel speed and dressing conditions are not changed. However, it has been reported before by other authors that wheel speed and the dressing conditions have a big influence on the proportion of the generated thermal energy transmitted to the workpiece [17]. As a result, even if the same value of E''_c can be produced with different grinding parameter combinations, the generated HPD could be different.

Moreover, the relationship between E''_c and HPD has only been studied before for the AISI 1045 steel. Thus, it has not been investigated whether a relationship exists between the physical properties of the hardened material and the correlation between HPD and E''_c.

In this study, it is proven that a relationship between E''_c and HPD exists during surface grind-hardening of 100Cr6, 42CrMo4 and AISI 1045 steels. Furthermore, the influence of wheel speed and dressing conditions on the E''_c–HPD relationship is analysed for AISI 1045 steel.

1.2.2. Prediction of the surface softening during finishing grinding

Even if the HPD has been achieved, grind-hardened workpieces present an inappropriate dimensional accuracy and surface finish. Thus, a final grinding operation is mandatory. During grinding, high temperatures could lead to workpiece softening, unfavourable residual tensile stresses or cracks that reduce its fatigue life. In the past, analytical and numerical models were developed in order to predict surface temperatures and support the process layout [18–20]. However, considerable difficulties have arisen when measuring grinding temperatures. Thermocouples and infrared radiation sensors have been used (among others), but extreme temperature gradients have made it difficult to obtain accurate temperature measurements and to validate the models.

Based on an analytical study, Malkin and Lenz proposed relating the maximum surface temperature to a maximum allowable specific grinding energy [21].

$$e_c = e_0 + CT_{max} d_s^{1/4} a_e^{-3/4} v_f^{-1/2} \tag{2}$$

where e_c is the specific grinding energy, e_0 is the 45% of the chip formation energy, C is a constant dependent on material properties, T_{max} is the maximum surface temperature, d_s is the wheel diameter, a_e is the depth of cut and v_f is the feed speed.

However, the wheel diameter and the actual depth of cut must be known during the grinding process. The need of these