Grind-Hardening

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Synonyms
Grinding hardening

Definition
Grind-hardening is a hybrid process that combines material removal and surface hardening of a steel workpiece at the same time. The heat dissipated in the cutting area is used for the heat treatment of the workpiece (Salonitis 2015a). For the grind-hardening of a workpiece, the generated heat in the interface between the grinding wheel and the workpiece material and the subsequent cooling of the material need to be controlled. The metallurgic change required for hardening thus is achieved in two steps: firstly, heating the workpiece surface above the austenitization temperature, and secondly afterwards rapidly cooling (quenching) the material for inducing martensitic transformation in the workpiece surface.

By using the grind-hardening process, several processing steps that are expected to take place when producing a component, such as conventional heat treatment, can be eliminated as shown in Fig. 1.

Theory and Application

The grind-hardening process was introduced by Brinksmeier and Brockhoff (1996). Initially, the process was investigated experimentally (Brockhoff and Brinksmeier 1999). Since then several studies have been published focusing on various aspects of the process such as the thermal analysis of the process (Salonitis and Chryssolouris 2007a), the importance of using and controlling the cutting fluid (Salonitis and Chryssolouris 2007b), the importance of selecting the most appropriate grinding wheel (Salonitis et al. 2008), the modeling and predicting of the grinding forces (Salonitis et al. 2014) and the residual stresses (Salonitis and Kolios 2015). A thorough review of the state of the art of grind-hardening process studies was presented by Salonitis (2015b), and up to that point more than 115 papers had been published in scientific journals and presented in referred conferences.

Grind-Hardening Process Mechanisms
Grind-hardening process goal is to surface harden the workpiece material while grinding. The surface hardening is a result of metallurgical changes in the material structure. The hardening mechanism is based on the phase transformation of

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The International Academy for Production Engineering et al. (eds.), CIRP Encyclopedia of Production Engineering, DOI 10.1007/978-3-642-35950-7_16848-1
austenite to martensite. The workpiece material (steel) before any heat treatment process has ferrite–pearlite structure (which exhibits a face-centered cubic geometry). During grind hardening, heat is generated due to friction in the interface between the grinding wheel and workpiece material (contact zone). As a result, heat flows from the contact zone into the workpiece, resulting in the increase of the surface temperature. When the temperature exceeds a critical temperature, the carbides in the lamellar pearlite begin to dissolve into iron. Further increasing the temperature, more of the carbides are dissolved until the steel consists completely of a solid solution of carbon in iron called austenite (in the form of face-centered cubic lattice structure geometry). These critical temperatures where the ferrite–pearlite transformations are initiated and finished depend on the carbon content of the steel and can be estimated from iron–carbon phase diagrams.

Such a crystal structure is characterized by higher strength, but cannot be sustained in ambient temperatures. If the workpiece material cools down in quasistatic mode, the austenite will be transformed back to ferrite–pearlite structure. For achieving high surface strength in lower temperatures, the austenitic phase needs to be transformed to martensite. By the rapid cooling of the workpiece material (quenching), the diffusion-dependent transformation that produces ferrite–pearlite is avoided, inducing non-equilibrium martensite structure.

The critical parameter in the quenching phase is the cooling rate that needs to exceed a critical value and depends on the carbon content of the workpiece material but also on the holding time above the austenitization temperature. For the case of grind-hardening, the required cooling is achieved through heat dissipation from the austenitized surface layer to the cooler workpiece material volume (characterized as self-quenching) and/or by using a coolant fluid (Salonitis and Chryssoulouris 2007b).
Grind-Hardening Parameters and the process outcome metrics (Salonitis 2015b) (With permission of Springer)

Grind-Hardening Process Parameters
The grind-hardening process as mentioned is used for the surface hardening of steel workpiece materials. The key metrics that need to be controlled, in many cases, are predetermined from the design phase, including the surface hardness, the hardness penetration depth (HPD), the residual stresses profile, the surface roughness, etc. The HPD is considered one of the most important variables to be controlled and is defined as the distance from the workpiece surface where the hardness value is reduced to 80% of the nominal value (Chryssolouris et al. 2005). These key metrics can be controlled through the proper selection of several process variables. These process variables can be considered as system parameters and some as grinding process parameters. The grinding process parameters are the typical ones for every grinding process, such as the cutting speed, the depth of cut, the feed speed, and the grinding fluid supply. The system parameters include the grinding wheel specifications, the grinding fluid, the workpiece geometry and material, and the machine tool to be used. Salonitis (2015b) summarized these parameters in Fig. 2.

The impact of all these parameters has been investigated thoroughly. Indicatively, for the grinding process parameters, there is a small process variable combination window that can lead to successful surface hardening. Several researchers have come up with process maps (e.g., Fricker et al. 2004 for the grind-hardening using CBN grinding wheels, and Salonitis et al. 2008) that can be used for selecting process parameters based on the design requirements. From the same figure, the effect of workpiece speed can be observed. For very low feed rates, the generated grinding power and thus
the generated heat is too low for increasing the workpiece temperature above the austenitization temperature. When increasing the feed rate, the generated heat and the HPD increase. A further increase of the feed rate results in shorter contact times leading to decreasing HPDs. Thus, maximum HPD can be achieved in for medium feed rates. Salonitis (2007a) has shown that the depth of cut is proportional to the specific material removal rate as well to the equivalent chip thickness. For constant specific material removal rate, an increase of the depth of cut results in deeper HPDs.

It is obvious that the grinding wheel operates in higher temperatures compared to conventional grinding. In some cases, temperatures exceed 1400°C. This has an impact on the grinding wheel lifespan. Higher operating temperatures result in higher wear rates for the grinding wheel and consequently to higher G-ratios. Furthermore, for the case of segmented CBN wheels, adhesives that connect the segments are deteriorating rapidly. Methods for reducing the temperature of the grinding wheel have been developed (as an example, the European Council funded FP5 project ENGY focused on developing new corundum and CBN grinding wheels that can withstand higher temperatures and also proposed methods for the direct cooling of the grinding wheel during the process (ENGY 2005)).

Grind-Hardening Applications
Brockhoff and Brinksmeier (1999) summarized the potential industrial applications. Since then, research has been conducted for increasing the maturity of the process. Lauwers et al. (2014) estimated the technological maturity level of various hybrid processes. Grind-hardening as process was classified as a process still in the concept development / prototype development. However, machine tool builders have already started considering grind-hardening as a process that they should provide solutions for.

The hardening capability of any workpiece material is a function of the chemical composition and the microstructure of the material. Thus, martensitic hardenable steels can be grind-hardened. The hardening result is determined by the carbon content and the content of alloying elements. The maximum surface hardness that can be obtained is approximately 60 HRC. As shown by Salonitis (2015) grind-hardening research has been conducted on all possible materials. However, most of the researchers have focused on AISI 52100 (equivalent to 100Cr6), AISI 1045 (equivalent to C45), AISI 1065 (equivalent to DIN 1.1230), AISI 4140 (equivalent to 42CrMo4), and AISI 5140 (equivalent to 37Cr4 or DIN 1.7035).

The workpiece geometry is also a limiting factor for the grind-hardening process. The process can be used for selectively heat-treating the surface of both cylindrical and prismatic parts. The key challenge though for using this process in workpieces with complex geometry is the tempering of the already heat-treated surface when the grinding wheel passes from the already grind-hardened area.

Cross-References
▶ Grinding
▶ Grinding Parameters
▶ Hybrid Processes

References
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