Influence of Cooling Condition on the Performance of Grind-hardening G C Wang¹,², J Chen¹, G Y Xu¹ and X Li¹

¹School of Mechanical Engineering, Jiangsu University, Zhenjiang, Jiangsu 212013, China
²Silicon Lake College of Vocational Technology, Kunshan, Jiangsu 215332, China

Abstract: 45# steel was grinded and hardened on a surface grinding machine to study the effect of three different cooling media, including emulsion, dry air and liquid nitrogen, on the microstructure and properties of the hardened layer. The results show that the microstructure of material surface hardened with emulsion is pearlite and no hardened layer. The surface roughness is small and the residual stress is compressive stress. With cooling condition of liquid nitrogen and dry air, the specimen surface are hardened, the organization is martensite, the surface roughness is also not changed, but high hardness of hardened layer and surface compressive stress were obtained when grinding using liquid nitrogen. The deeper hardened layer grinded with dry air was obtained and surface residual stress is tensile stress. This study provides an experimental basis for choosing the appropriate cooling mode to effectively control the performance of grinding hardened layer.

Keywords: Grind-hardening; Cooling condition; Microstructure; Hardness; Residual stress

1. Introduction

In the process of grind-hardening, workpiece surface temperature increases to austenitizing temperature in short time due to violent extrusion and sliding motion between grinding wheel and workpiece and then were quickly cooled down, so that workpiece surface layer transform to martensite[1]. Cooling is an essential part of the grind-hardening process, and cooling mode has an important impact on the formation and performance of grinding hardened layer. Therefore, based on the grind-hardening process, experiments were conducted in this research, in order to study the influences of three different cooling media, such as emulsion, dry air and liquid nitrogen, on the microstructure and properties of the hardened layer. This study provides theoretical and experimental
guidance for selecting appropriate cooling method and effectively controlling the quality of grind-hardening process.

2. Cooling methods and features

The purposes of cooling in grinding surface between grind-hardening process and ordinary grinding are different. Ordinary grinding process aims to reduce the grinding temperature for avoiding grinding burn, so the jet cooling area is set in front of wheel-workpiece contact surface, as shown in Figure 1a, to facilitate the cooling medium into the arc zone [2]. In grinding hardened process, grinding energy is used to heat the workpiece, and then cooling, therefore the machined surface behind the wheel-workpiece contact surface is regared as the cooling area, as shown in Figure 1b. Providing cooling medium for the machined surface of the workpiece aim to obtain hardened surface and reduce temperature of the grinding wheel for longer service life [3].

![Figure 1. Comparison between jet area of cooling](image)

(a) Ordinary grinding  (b) Grind-hardening

The purposes of quenching are to obtain martensite, but also to prevent the decomposition of undercooled austenite. Therefore, greater degree of undercooling is needed to endure that cooling rate greater than the critical cooling rate Vc. The curve C shows that the nose temperature is about 500°C ~ 600°C. Therefore, there is no need for rapid cooling when the workpiece is cooled below nose temperature of the curve C. In addition, slowly cooling process in the martensitic transformation zone can reduce the structure stress, contributing to small deformation and fewer cracking [4]. Therefore, hardening medium in grind-hardening should be characterized by rapid cooling at medium temperature region (500-600°C) and slow cooling at low temperature area (Figure 2). In addition, the cooling medium should also meet these requirements that there are no or less harmful oxidation, reduction reactions or other physicochemical reactions between cooling medium and workpiece material, the workpiece surface is not contaminated or less contaminated. It should ensure that it is easy to operate and recycle, non-toxic, low cost. Commonly used mainly are emulsion, dry air and liquid nitrogen are three main kinds of grind-hardening cooling medium.
Figure 2. Cooling curve of ideal quenching medium

Emulsion is the mixture of water and emulsified oil, which contribute to lower cooling rate, increasing stability of the steam film and boiling stage happened in the low temperature area. Emulsion is not easy to degenerate and has longer service time and good rust. Air medium has slower cooling rate and boiling temperature of air is much higher than that of workpiece. Therefore, under normal circumstances, there are no boiling and material changes when cooling, but also, cooling curve shows a steady state. At high temperatures, radiant heat is its main form; convective heat transfer is its predominant form at low temperatures. By using compressed air, cooling rate can be increased several times, better cooling uniformity and hardness uniformity are obtained.

Cooling strength and rate of liquid nitrogen are much greater than that of the emulsion. Cooling process using liquid nitrogen does not result in three stages of thermal shock compare to ordinary medium, and the possibility of workpiece deformation and crack are much lower. In addition, martensitic transformation proceeds more completely when quenching using liquid nitrogen, with minimal retained austenite and martensitic microstructure. Higher hardness, wear resistance and dimensional stability are obtained.

3. Grinding experimental conditions and parameters

3.1. Experimental Materials
AISI1045 with a size of 45×19.5×19.5 mm was selected as the experimental material. The heat treatment method is a anneal above 600 °C in vacuum. The initial surface residual stress is -10.00±8.00 MPa (longitudinal direction) and -10.39±8.00 MPa (transverse direction), and the hardness is HV0.5 172.9 ± 11.1.

3.2. Grinding process conditions
Grind-hardening cooling experiments were performed on the Minini Junior 90 CF M286 CNC grinding machine and the workpieces were ground using BWA60MVA1 grinding wheel. The grinding wheel speed is vs=23 m/s, the workpiece feed rate is vw=400 mm/min and the cutting depth is ap=20 µm. Cooling experiments were conducted by using three different cooling methods, including dry air with an ambient temperature of 20 °C, liquid nitrogen (Q=2.18L/min) And an emulsion (Noritake SA-02 (1:60), Q=18.8 L/min).
3.3. Texture and performance testing
The hardness of the grinding surface was measured using a microhardness tester Shimadzu Seisakusho NT-M001. The ground surface topography was observed with a scanning electron microscope (SEM). Gradient residual stress were obtained by using the Movipol-3 electrolytic polishing machine and the X-ray stress analyzer MSF-3M. Transmission electron microscopy (TEM) was used to observe the microstructure of the ground surface.

4. Test results and analysis

4.1. Influence of cooling medium on the surface morphology
Figure 3 shows different surface morphologies hardened with different cooling media. As shown in figure 3a, the workpiece surface cooled by emulsion is a continuous slot with the surface roughness of Ra=0.25μm. The surface was bright and not oxidized. Figure 3b shows grinding surface topography using dry air as cooling medium, workpiece surface appears a darker oxidation color with a surface roughness of Ra=0.98μm. It is obvious that the split groove caused by the lack of lubrication, and spherical particles which is the form of melting grindings in grinding surface, further reducing the grinding surface quality [5]. Grinding surfaces using liquid nitrogen as cooling conditions are showed in Figure 3c, the specimen surface is bright without any oxidation or burns and the surface roughness of Ra=0.27μm, indicating that oxidation is inhibited and liquid nitrogen played an important role to protect the surface.

Figure 3. Workpiece surface topograph in different cooling conditions
(a)Emulsion  (b)Dry air  (c)Liquid nitrogen
4.2. Influence of cooling medium on the microstructure

Optical micrographs of subsurface regions of the specimen under different cooling conditions were studied. The hardened layer did not occur under emulsion cooling conditions and the material microstructure is regard as pearlite.

Grind-hardening layers were present in the test pieces under dry air or liquid nitrogen cooling conditions. In the dry air cooling condition, grind-hardened layer is irregular martensite with the depth of 350μm. Compared with the lath martensite produced by ordinary heat treatment, the structure of this martensite layer is finer [6]. This is due to the fact that grinding-hardening is the combined effect of grinding heat and grinding forces during grinding process. As the grinding heat transfer in the sample, the temperature of contact area between grinding wheel and workpiece surface reaches above Ac3 which contribute to austenization, martensite generated during cooling process in the meanwhile, workpiece surface deformed due to grinding force. The dislocation density also increases while the grain is shredded, which leads to grain refinement [7]. At the bottom of the hardened layer, there are many ferrite grains with carbides precipitated at the boundaries.

With liquid nitrogen cooling condition, grinding hardened layer will be thinner with depth of only 85μm. The reason is that the reduction of the surface heating temperature and the increase of the temperature gradient sharply reduce the area at a temperature above Ac3, which eventually leads to a corresponding decrease in the depth of the hardened layer. The martensitic structure at the bottom of the hardened layer is smoother and it is difficult to distinguish it from hardened layer under dry air cooling condition using optical microscope.

4.3. Influence of cooling medium on the microhardness

The microhardness of the hardened layer was not changed (HV(500g)=200) under the cooling condition of the emulsion. Under dry air conditions, the microhardness of the grinding hardened layer increased to HV(500g)=750, which is 3.75 times higher than that before processing and 1.15 times of ordinary martensite (HV(500g)=650). The hardness of the grinding hardened layer shows a gradient change. The hardness at the bottom of the hardened layer decreases to HV(500g)=400 due to its changes of microstructure to a ferrite-carbide arrangement. Under the condition of liquid nitrogen cooling, the hardness of the grinding hardened layer is the highest, up to HV(500g)=1100, which is 1.46 times of the microhardness of the sample in dry air. In addition, the microhardness decreases slightly with the thickness of the ground hardened layer, martensite occurs at the bottom of the hardened layer with a hardness as high as HV(500g)=700. Liquid nitrogen cooling has a greater gradient than the air-cooled temperature field, more complete martensitic transformation and very little retained austenite result in higher hardness.

4.4. Influence of cooling medium on the residual stress

The distribution of residual stress on the subsurface of the grinding workpiece is studied. Residual stresses σxx and σyy are respectively measured along the grinding direction and the vertical direction. Under the condition of emulsion cooling, the workpiece is residual compressive stress in both directions within a depth of 100 μm, with a size of 200-400 MPa. In dry air, in the level of the workpiece hardened layer depth (400μm), residual tensile stress occurs in the direction of XX and YY, with the magnitude of 100 ~ 200MPa. The residual compressive stress generated by the liquid nitrogen
cooling grinding of the workpiece is 200 MPa, distributed at a depth of 85 μm, which is similar to the emulsion cooling. Grinding hardened layer residual stress is the result of the combined effect of mechanical stress, thermal stress and phase transformation stress [8]. When using the emulsion as cooling medium, the thermal stress decreases, and the surface residual stress value develops toward the direction of compression, which is the main reason that the surface has a large residual compressive stress.

5. Conclusion
(1) Using dry air as the cooling medium, the workpiece surface roughness is much larger and oxidation occurs, and the use of emulsion and liquid nitrogen as a cooling medium, the workpiece surface roughness is smaller and no oxidation occur.
(2) In the condition of emulsion cooling, the workpiece surface structure is pearlite and no hardened layer. In dry air or liquid nitrogen cooling conditions, the surface structure of the workpiece is martensite and hardened layer occurs. Compared to liquid nitrogen cooling condition, the depth of the hardened layer on the workpiece surface under the condition of dry air cooling is deeper.
(3) The hardness of the surface layer after the workpiece was cooled by emulsion is not changed. The hardness of the workpiece hardened layer under liquid nitrogen cooling was harder than that of the ground hardened layer under the condition of dry air cooling, and the hardness of the former did not change obviously with the depth of the hardened layer. The latter hardness changes obviously with the depth of hardened.
(4) In the emulsion and liquid nitrogen cooling conditions, the residual stress in the hardened layer of the workpiece are residual compressive stress, but tensile stress in dry air conditions, which will lead to the workpiece fracture, fatigue failure, corrosion and wear.

Acknowledgment
This research was supported by the Natural Science Foundation of P. R. China (No. 51075192), National key projects of P. R. China (2013ZX04009031) and A Project Funded by the Suzhou City key laboratory of elevator safety technology.

References
[1] J D Liu, G C Wang 2003 Modern Manufacturing Engineering 11 pp 81-83
[2] J X Ren, D A Hua 2011 Grinding Principle (Beijing: Publishing House Of Electronics Industry)
[3] J D Liu, G C Wang 2004 Tooling Engineering 37 pp 11-14
[4] G C Wang 2015 Grind-Hardening Technology (Beijing: National Defence Industry Press)
[5] L Q Wu, Y Qin, D Qian 2013 Ordnance Material Science and Engineering 36 pp 138-140
[6] J D Liu, G C Wang 2004 Tool Engineering 38 pp 67-69
[7] K M Liu, Z Ma 2012 Hot Working Technology 41 pp 215-217
[8] J D Liu, D P Hou 2008 Heat Treatment of Metals 33 pp 127-130