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# Grinding-hardening with liquid nitrogen: Mechanisms and technology

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**Abstract**

This paper studies an innovative development of a steel grinding–hardening technology using an inert cryogen—liquid nitrogen. It was found that phase transformations took place during grinding with the application of liquid nitrogen and resulted in hardened surface layer in a ground component. The layer had a fine laths martensite structure which gave rise to a remarkably high hardness. It was also shown that the treatment can produce superior surface integrity, with compressive surface residual stresses and without surface oxidation. Due to the inert nature of the liquid nitrogen, the grinding process becomes environmentally conscious.


*Keywords:* Grinding liquid nitrogen; Microstructure; Residual stresses; Hardness; Phase transformation; Oxidation suppression

## 1. Introduction

Grinding–hardening treatment has attracted significant research attention worldwide due to its efficiency and unique properties of ground workpiece [1–7]. Relevant theoretical and experimental studies have shown clear advantages of grinding–hardening which combines surface heat treatment with surface finishing.

In the investigations on grinding-induced surface integrity in steel workpieces [8,9], it was found that phase transformations during surface grinding, which in turn resulted in hardening characteristics, could be achieved by a proper selection of grinding conditions. It was also found that the depth and property of the martensite layer and the distribution of residual stresses could be described quantitatively with respect to the material removal rate and coolant application method.

Experimental studies also reported that the grinding energy could be used to generate a hard surface [1,2,6]. However, a hardened layer does not necessarily mean beneficial, rather, it can be harmful if the layer is associated with a poor surface finish, uncontrollable precision, tensile residual stresses, damaged microstructure or severe surface oxidation [5,6].

One way to eliminate these problems is by applying new types of coolant. It has been noticed that in the field of welding, oxidisation is one of the major causes in weakening the strength of welds. To overcome the problem, nitrogen gas has been used in shielding the welding spot [10]. On the other hand, liquid nitrogen, because of its extremely low boiling temperature, has been widely applied in cryogenic treatment of tool steels to convert austenite retained from conventional quenching to a more rigid structure of martensite [11–16]. It is clear that liquid nitrogen whilst acts as a protective shielding, can also provide high cooling rates to promote metallurgical changes. However, these advantages have not been explored in grinding.

This paper proposes an innovative development of grinding–hardening technology using liquid nitrogen to integrate precision surface grinding with surface hardening treatment, and at the same time, to produce satisfactory surface integrity of ground components, including compressive surface residual stresses and fine microstructure with high hardness. Because of the inert nature of liquid nitrogen, the grinding process becomes environmentally conscious.

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Table 1
Chemical composition and mechanical properties of steel 1045

| Chemical compositions, % | | | | Mechanical properties | | |
|---|---|---|---|---|---|---|
| C | Mn | *P*, max | *S*, max | Tensile strength (MPa) | Micro-hardness ($HV_{0.5}$) | Yield strength (MPa) |
| 0.42–0.50 | 0.60–0.90 | 0.040 | 0.050 | 630 | $172.9 \pm 11.1$ | 530 |

Table 2
Grinding and dressing conditions

| | |
|---|---|
| Grinding machine | Minini Junior 90 CNC-M286 |
| Workpiece | • Plain carbon steel 1045, $45 \times 19.5 \times 19.5$ mm<br>• Vacuumed pre-annealing at above 600 °C<br>• Initial surface residual stress: $-10.00 \pm 8.00$ MPa (longitudinal) and $-10.39 \pm 8.00$ MPa (transverse) |
| Grinding method | Surface up grinding |
| Grinding wheel | BWA60MVA1, $\phi 260 \times 20$ |
| Dressing | • Single point diamond<br>• Transverse rate = 160 μm/rev<br>• Total dressing depth = $2 \times 25$ μm |
| Wheel speed | 23 m/s |
| Table speed | 400 mm/min |
| Depth of cut | 20 μm |
| Cooling | Atmospheric dry air, ambient temperature = 20 °C<br>Liquid nitrogen, $Q = 2.18$ L/min<br>Noritake SA-02 (1:60), $Q = 18.8$ L/min |

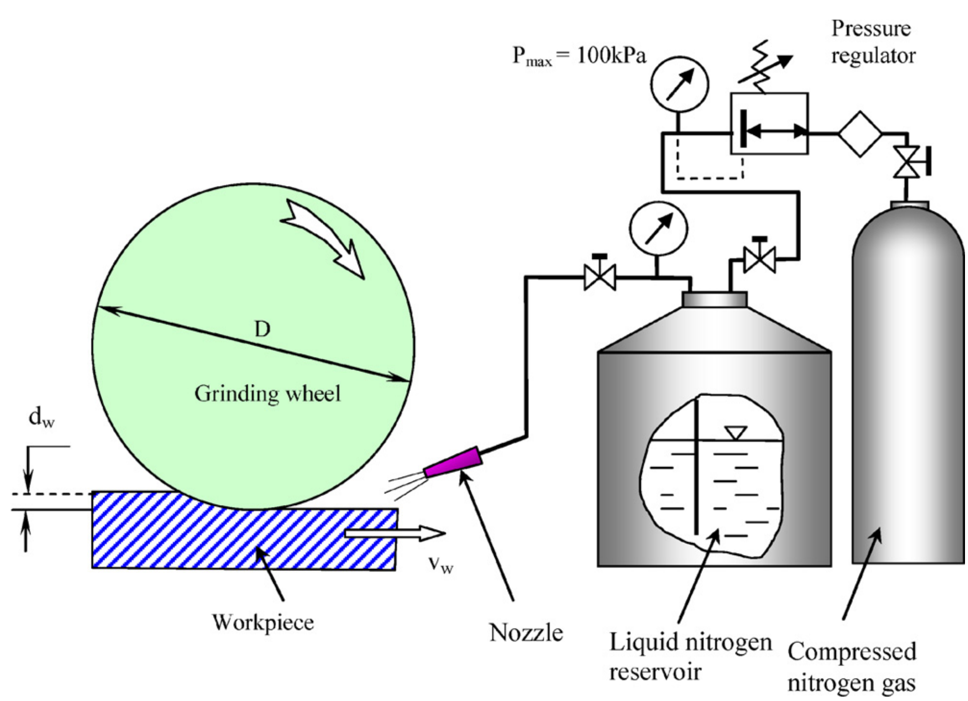


Fig. 1. The experimental set-up using liquid nitrogen.

## 2. Experiment

The test material was widely used steel, AISI 1045, initially annealed. The chemical composition of the steel is listed in Table 1. Grinding was performed on a surface grinder, Minini Junior 90 CF CNC M286. The grinding and dressing conditions are listed in Table 2.

Fig. 1 shows the experimental set-up of surface grinding with liquid nitrogen. The internal pressure of the reservoir was 50 kPa, controlled by a regulator. A nozzle with the