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# The evolution of hardness and tribofilm growth during running-in of case carburized steel under boundary lubrication

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ABSTRACT

Many newly manufactured components are subject to a run-in procedure. The objective of this study was to understand how the surface hardness of 16MnCr5 bearing steel evolved during running-in and how varying contact pressure and initial composite roughness affected this evolution. The evolution of the tribofilm formed by zinc dialkyl dithiophosphate (ZDDP) and how it contributed to the measured hardness was also analyzed. The results indicated a higher initial composite roughness led to greater gains in hardness as compared to higher contact pressure during the running-in process. Tribofilm growth appeared to have little to no significant effect on the measured surface hardness increase during running-in and the primary contributor to the observed hardness increase was work hardening.

## 1. Introduction

Running-in is the initial wear and plastic deformation of interacting surfaces, starting with the conditions after manufacturing. It is understood that run-in is achieved when a steady-state of friction or mild wear is reached. The transformation of wear and friction are characterized by changes in the thin surface layer's conformity, oxide film formation, material transfer, lubricant reaction product, martensitic phase transformation, and subsurface microstructure reorientation [1]. However, there is a gap in understanding all the changes which occur during in the initial phases of running-in which was identified by Blau [2]. Much of the research performed still has not fully characterized the details of run-in and yet run-in is often utilized as a starting procedure for tribotests [3–5]. If engineers fully understood the running-in process it would be invaluable in enhancing the operation and extending the life of tribosystems.

One aspect of running-in which has been studied extensively is the change in surface roughness. Abbott and Firestone's work initially sparked the drive to understand the topography changes of surfaces during run-in when they characterized the asperities which come into contact with one another [6]. Anderson determined running-in occurred at around 300,000 cycles when observing the wear of asperities and the surface roughness [7]. Research by Martins et al. showed a significant smoothening of asperities occurred after 90,000 cycles under a low load [8]. Akbarzadeh and Khonsari indicated asperities are flattened and the valleys are mostly unchanged [9]. This was further indicated by Sosa et al. [10]. Researchers who study the roughness during run-in show transformations in Ra, Rmax, Rku, Rq, and Rsk [11,12].

Instead of attributing the reduction in asperity peaks to abrasive or mild wear during the initial stages of running-in, Berthe et al. analyzed the surface mechanics of the asperities during running-in and showed the plastic deformation stabilized after ten cycles [13]. Mallipeddi et al. also observed surface asperities were reduced due to plastic deformation [14]. Zwirlein and Schlicht observed compressive residual stresses could be generated through cyclic stresses and strengthen the subsurface [15]. Burbank and Woydt sought to utilize the running-in as a controlled work hardening and observed increased operational lifetimes for different steel types [16].

Zinc dialkyl dithiophosphate (ZDDP) is an anti-wear agent present in most automotive lubricants blends and reduces wear and scuffing between metal surfaces by forming a boundary film (tribofilm) [17,18]. A study by Aktary et al. indicated tribofilms develop rapidly (5 min) after rubbing tests on 5210 steel [19]. Parsaeian et al. measured the tribofilm growth under varied humidity conditions and showed, for all conditions, the tribofilms reached a maximum thickness between 20 and 30 min of rolling-sliding contact [20]. Work by Kalin et al. showed the ZDDP tribofilm hardness properties evolved as a function of test duration and had measurable hardness after 25 min [21].

Previous work by Wagner et al. paralleled this immediacy of run-in Ref. [22]. Wagner et al. also showed evidence of hardness gains within

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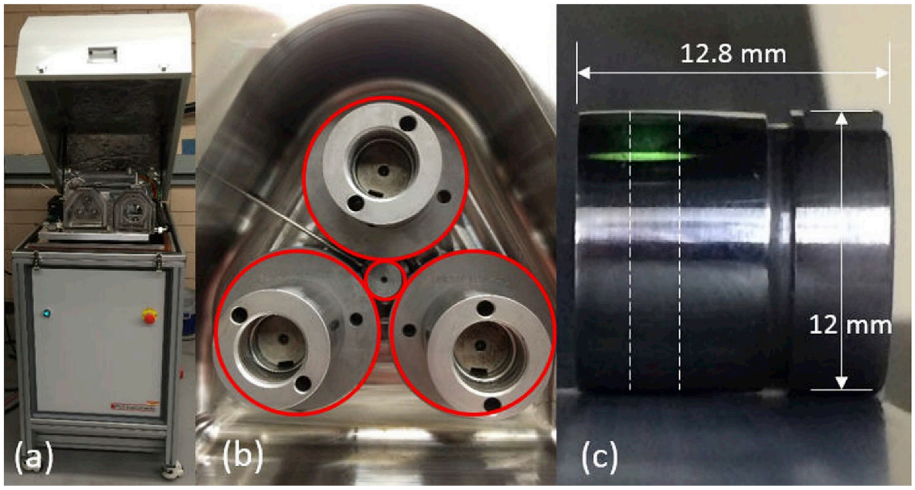


**Fig. 1.** (a) Micro Pitting Rig (MPR) used in this study, (b) test chamber showing the central roller (sample) and three rings, and (c) dimensions of the roller. Dashed lines indicate approximate contact zone.

**Table 1**
Test sample roughness and contact load conditions (replicates were made for each condition except A).

| Test | Load (N) | Pressure[a] (GPa) | Composite Roughness,[b] Ra (μm) | Composite Roughness,[c] Rq, (μm) | Lambda Ratio[d] (λ) | Lubricant (API Group II Base Oil) |
|---|---|---|---|---|---|---|
| A | 90.6 | 1 | 0.20 | 0.17 | 0.118 | *with* ZDDP additives |
| B | 724.7 | 2 | | 0.18, 0.18 | 0.095, 0.094 | |
| C | 90.6 | 1 | 0.47 | 0.53, 0.54, 0.52 | 0.038, 0.037, 0.039 | |
| D | 724.7 | 2 | | 0.53, 0.54 | 0.032, 0.032 | |

[a] Max Hertzian pressure.
[b] Calculated per manufacturer's specifications.
[c] Calculated per measured initial surface roughness.
[d] Based on Hamrock-Dowson minimum film thickness (Equation (1)).

**Table 2**
MPR conditions used for all tests. Parameters resulted in boundary lubrication for all conditions.

| Parameter | Value |
|---|---|
| Time | 150 minutes |
| Contact Cycles | 109,669 cycles |
| SRR (Eq. (1)) | 20% |
| Entraining Velocity | 0.17 m/s |
| Spin-off Temperature[a] | 80 °C |

[a] Spin-off Temperature was measured by a temperature probe inserted into the test chamber with the tip of the probe placed close to the contact region.

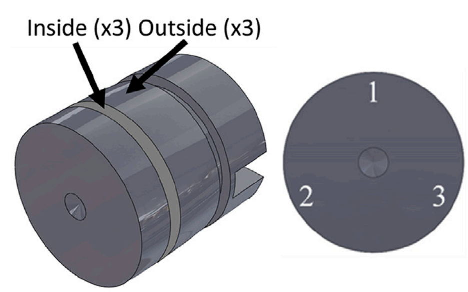


**Fig. 2.** (Left) Locations for hardness measurements inside and outside wear track. (Right) Circumferential locations for hardness measurements.

**Table 3**
Geometric and material properties of roller and ring components used in testing.

| Property | Value |
|---|---|
| Roller radius (x) | 12 mm |
| Roller radius (y) | 76.2 mm |
| Ring radius (x) | 27 mm |
| Ring radius (y) | ∞ (flat) |
| Elastic modulus | 205 GPa |
| Poisson ratio | 0.29 |

the contact region following approximately 110,000 cycles. It was shown that run-in occurs at a relatively low number of contact cycles and hardness gains are present in this time frame as well, and it was proposed work hardening develops early on within the same number of cycles.

The purpose of this study was to characterize the evolution of hardness during the early stages of running-in of 16MnCr5 steel for a specific combination of slide-to-roll ratio (SRR), entraining velocity, oil spin-off temperature, and oil/additive package. The effect of contact pressure and initial composite surface roughness on the hardness evolution were also studied. Tribofilms can develop on steel surfaces during rolling-sliding contact, so energy-dispersive X-ray spectroscopy (EDS) point analysis was used to detect the presence of a tribofilm within the wear track region. Since tribofilms might influence the measured hardness, an attempt to characterize the hardness gains as a combination of work hardening and the influence of the presence of tribofilms was also explored. The results of this study cover the application of interest (gears and rolling element bearings in off-road equipment), so the effect could be different for different conditions.

## 2. Experimental methods and equipment

### 2.1. Run-in testing

Tests performed in this study were run using a Micro Pitting Rig