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# Friction and anti-galling properties of hexagonal boron nitride (h-BN) in aluminium forming

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A B S T R A C T

In the present work the friction and anti-galling properties of the h-BN in a steel-aluminium contact have been investigated, focusing on the possibility of replacing graphite with the h-BN in the aluminium forming operations. Extruded AA2014 alloy, widely used for the production of complex parts, was used. Investigation included the effect of h-BN powder size and concentration on the level and stability of the coefficient of friction, galling resistance and the quality of the Al surface. Tribological and anti-galling properties at room and elevated temperature of 400 °C have been carried out on the load-scanner test rig. Graphite was used as a reference solid lubricant. In the case of the h-BN powder three different particle sizes were used, i.e., 0.5 µm, 5 µm and 30 µm, added to NGL class-2 industrial grease in the concentrations of 5%, 10% and 20%. Results show that white h-BN, as a solid lubricant, is capable of successfully replacing graphite and providing "clean" surface, but only under mild contact conditions. It has similar lamellar structure but inferior load-carrying capacity, with its lubrication and anti-galling properties very much depending on the powder size, concentration and temperature. Contrary to the graphite tribological properties of h-BN deteriorate with increased concentration but improve with temperature and powder size. Best results are obtained for concentration of 5% and 30 µm powder size.

## 1. Introduction

In metal forming operations lubricants are essential, not only to reduce friction and effect stress and strain distribution, but also to reduce tool wear, increase the forming limit, improve workpiece surface quality and to ease the release of the finished part [1–3]. Hence, lubrication is critical, especially in hot metal forming. Inadequate lubrication or a breakdown of the lubrication film will cause direct contact between workpiece and the die, followed by transfer and build-up of the softer workpiece material on the tool surface, also known as galling [4]. Galling is a common problem in forming applications that may change the tool geometry, increase the friction force, cause tearing in a severely strained area and lead to workpiece rejection [5]. Several parameters are known to affect galling, with the risk of galling being reduced by decreasing tool surface roughness, minimizing sliding distance, decreasing contact pressure, using low friction coating or by addition of lubricants [6,7].

Automotive industry makes ever increasing demands on reduced weight of car chassis and components thus resulting in extensive use of light-weight materials, including aluminium, magnesium and titanium alloys [8]. Especially aluminium-based alloys present a number of interesting properties, such as low density, corrosion resistance, thermal conductivity, recyclability and good mechanical properties [9]. However, the formability of these metals is lower and much more demanding than that of steel [8,9]. They are also very prone to adhere to the tool's bearing surface [10]. The tribological mechanisms taking place during forming of light metals are very complex and can involve adhesion, mechanical interaction of surface asperities, ploughing, deformation and fracture of surface oxide layers [10,11]. These mechanisms usually act simultaneously, thus posing considerable challenge and requirements also from the lubrication point of view [3,12]. Therefore, simultaneous development in surface engineering and forming lubricants is crucial [13].

In cold forming lubrication is mainly based on liquid lubricants, which can be water- or oil-based [14]. However, commonly used metal forming lubricants are often flammable, contain active hazardous elements and often require additional cleaning procedures and solvents for removal from the formed surface. Post-cleaning and disposal of these lubricants and solvents can be difficult, costly and environmentally unfriendly [1]. On the other hand, hot metal forming operations

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make extensive use of solid lubricants which are less demanding from the application point of view. Beneficial action of solid lubricants is mainly related to the lamellar structure and softness of these materials [15]. The most extensively used solid lubricant, found in almost all hot forming applications is graphite, followed by $MoS_2$, which is due to their low cost, availability and excellent lubrication performance. However, graphite needs moisture for good lubricity, finally resulting in a very dirty and potentially harmful environment [16]. Both, graphite and $MoS_2$ are also black in colour and may leave dark stains on the formed surface, which can lead to parts rejection. Lubrication properties of graphite and $MoS_2$ have been extensively investigated, explained in detail and well documented [15,17]. However, there are also other compounds with similar structure which were recognized as the potential solid lubricants [18].

Different studies indicate [1,19–21] that the boron based compounds such as the hydrogen borate, borate esters, boric acid and alkali-borates are among the best lubrication additives when it comes to forming aluminium alloys. They exhibit very low friction as a consequence of low friction layers generated by tribochemical reaction and show strong interatomic bonding and rigidity of layers thus preventing scuffing and galling. Boric acid for example was found to form chemically bonded films on the oxidized surface of aluminium and its alloys [1]. Another low friction boron compound is a hexagonal boron nitride (h-BN). The h-BN also has a lamellar crystalline structure which is similar to those of graphite and $MoS_2$, but is white in colour and superior in terms of thermal stability [22]. In the h-BN lamellar structure the bonding among molecules within each layer is covalent, whereas the bonding between adjacent layers are weak Van der Waals forces [23]. This kind of structural properties of the h-BN provides easy shear along the basal plane of the h-BN. It was also found that even single-layer h-BN can show low friction [24]. These properties make the h-BN a good solid lubricant candidate. Although h-BN micro- and nanoparticles are well-known solid lubricant additives providing low friction and slow wear rate [15,19,25], not many reports exist on the performance of the h-BN in a high temperature forming applications.

The aim of the present work was to determine friction and antigalling properties of the h-BN in steel-aluminium contact at room and elevated temperature and to investigate the effect of h-BN powder size and concentration. Special focus was on the possibility of replacing graphite with white h-BN in aluminium forming application's, which would not require additional cleaning and polishing operations.

## 2. Experimental

### 2.1. Materials and lubricants

Al-alloy used in this investigation to evaluate lubrication and antigalling properties of h-BN was extruded AA2014 alloy with a hardness of 135 HB (Wolpert Dia testor 3b). It is a high strength aluminium alloy used for complex machine parts. The chemical composition of the alloy was the following (mass content in %): 93.02% Al, 0.07% Cr, 4.30% Cu, 0.18% Fe, 0.74% Mg, 0.88% Mn, 0.72% Si and 0.09% Zn. Specimens in the shape of discs (ϕ42 × 8 mm) were cut from the extruded bar and the surface was polished to an average surface roughness ($R_a$) of ~0.05 µm. As a counter material a hardened DIN 100Cr6 bearing steel balls (ϕ10 mm) and vacuum heat treated Dievar hot work tool steel (Böhler Uddeholm) cylinders (ϕ10 × 100 mm) were used. 100Cr6 steel balls were commercial bearing balls with a hardness of 60 HRC and roughness $R_a$ = 0.02 µm. Hot work tool steel cylinders (0.35% C, 0.2% Si, 0.5% Mn, 5.0% Cr, 2.3% Mo, 0.6% V) were first vacuum heat treated, using austenitizing temperature of 1000 °C and double 2 h tempering at 610 °C, followed by fine surface grinding and polishing. Vacuum heat treatment and polishing resulted in cylinders hardness of 46 HRC (Rockwell 4JR, Instron B2000) and average roughness ($R_a$) of 0.10 µm, properties typical for Al-forming dies.

As the base lubricant, a commercially available lithium-based NLGI class 2 grease was used, made from the lithium 12-hydroxy-stearate thickener, high-quality mineral oil, corrosion inhibitors and antioxidants. Base grease had a dropping point of 190 °C and density of 940 kg/m$^3$. Natural graphite powder with 96% purity and an average particle size of ~5 µm was used as a reference solid lubricant, which was mixed with the base grease in 5%, 10% and 20% concentrations, respectively. In the case of the h-BN solid lubricants, commercial powders with 98.5% purity (Lowerfriction Lubricants, Canada) were employed, using three different particle sizes; 0.5 µm, 5 µm and 30 µm. All h-BN powders were found to be highly crystalline with all peaks of hexagonal boron nitride and complete three-dimensional ordering, as shown by the XRD analysis [21]. The h-BN powders were then mixed with the base NLGI-2 grease in concentrations of 5%, 10% and 20%, respectively. Mixing of the solid lubricant powder into the base lithium grease was done manually, preheating grease to 50 °C and stirring for about 10 minutes. For all mixtures uniform distribution without solid particles agglomeration was obtained. The lubricants' designations and description are given in Table 1.

**Table 1**
Description of lubricants used in the investigation.

| Solid Lubricant | Particle size | Concentration | Designation |
|---|---|---|---|
| Base NLGI-2 grease | | | L |
| Graphite | 5 µm | 5% | G-5 |
| | | 10% | G-10 |
| | | 20% | G-20 |
| h-BN | 0.5 µm | 5% | B05-5 |
| | | 10% | B05-10 |
| | | 20% | B05-20 |
| | 5 µm | 5% | B5-5 |
| | | 10% | B5-10 |
| | | 20% | B5-20 |
| | 30 µm | 5% | B30-5 |
| | | 10% | B30-10 |
| | | 20% | B30-20 |

### 2.2. Tribological testing

The most typical standard test methods used in the evaluation of solid lubricants are four-ball method for wear preventive characteristics determination (ASTM D2266), Timken method for measurement of load-carrying capacity (ASTM D2509), Falex pin and vee method for endurance life and load-carrying capacity determination (ASTM D2625), test methods for wear life and wear preventive properties of lubricating greases using (Falex) block-on-ring test machine (ASTM D2981 & ASTM D3704) and test method for measuring friction and wear properties of lubricating greases using a high-frequency linear-oscillation (SRV) test machine (ASTM D5707). However, all these methods focus solely on properties of solid lubricants and facilitate use of standard steel specimens. In order to more closely simulate real Al-alloy/steel contact two non-standard test methods were used in this investigation. Lubrication properties and effect of the h-BN powder size and concentration on the coefficient of friction and wear rate at room temperature were investigated using low-frequency reciprocating sliding ball-on-flat contact configuration (Fig. 1a). In reciprocating sliding tests the 100Cr6 steel ball was loaded against the stationary Al-alloy disc, with the lubrication grease containing solid lubricant particles applied on the disc surface prior the test. Tests were performed for 10 min at a frequency of 2.5 Hz and amplitude of 10 mm, which resulted in an average sliding speed of 0.05 m/s and total sliding distance of 30 m. Testing load was 4.5 N, corresponding to a maximum Hertzian contact pressure of 500 MPa. The test results and lubrication performance of the h-BN at room conditions were evaluated in terms of the average coefficient of friction and the Al-alloy disc wear volume and wear rate, measured by 3D white-light optical interferometry (Alicona, InfiniteFocus G4).