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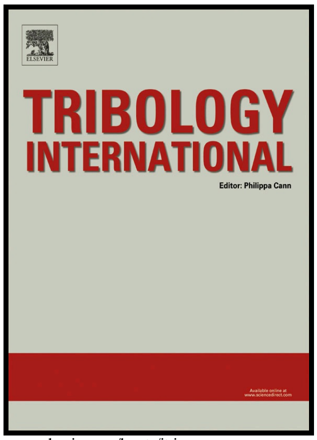

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Diverse mechanisms of friction induced self-organisation into a low-friction material – an overview of WS_2 tribofilm formation

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ABSTRACT
A clever way to accomplish low friction in sliding contacts is to use materials that combine high hardness with low shear strength. Such seemingly paradoxical combination of high resistance and low resistance to plastic deformation can only be realized by combining a hard substrate material with a thin easy-shear coating. Some prominent such coating candidates are sulfides and selenides of mainly molybdenum and tungsten. This paper focuses on tungsten disulfide, WS_2, and explores the many routes to formation and regeneration of such low-friction tribofilms. The initial surfaces involve various types of coatings, materials and fluids, including W and S in different states, but none of which include crystalline WS_2. All formation routes result in remarkably similar, pure crystalline WS_2 tribofilms.

1. Introduction

1.1 Introduction to low-friction coatings

Smooth, quiet sliding motion with low energy loss requires low friction. If cases where no lubricant is applied, low friction requires the combination of a low shear strength interface and a small contact area to shear. This demands a material that combines being soft with being hard; the high hardness to facilitate the small contact area and the softness to offer the low shear strength. Such a combination cannot be offered by any homogeneous material known, so the traditional solutions are based on using a hard substrate material and topping that with a thin film that offers the low shear strength interface; a soft metal, an oxide, a diamond like carbon coating (DLC), etc.

In many systems, lubricants such as oils or greases cannot be used, e.g. due to the risk of contamination of food, medicines, chemicals, optics, or other sensitive goods. Further, these lubricants are often not useful in vacuum, other extreme environments or at extreme temperatures. Finally, in many applications the presence of a lubricant cannot be guaranteed in all situations, including cold starts, temporary lubricant supply problems, for parts with minute amplitude oscillatory motion, and more. In all these cases, low-friction, wear resistant coatings may be the best solution. The most prominent and most investigated candidates are DLC´s, plus a few materials belonging to the group transition metal dichalcogenides (TMD). The TMD family of low-friction materials includes MoS_2, WS_2, $MoSe_2$, WSe_2 and $MoTe_2$. The last of these is still rare and has not been widely investigated. The TMD family also includes several other compounds, sharing the same hexagonal structure, but without the certain electronic structure with filled d-orbitals that results in an intrinsic easy-sheared structure [1,2]. DLC is an even larger family of coatings based on amorphous carbon. Often DLC´s are alloyed with hydrogen and/or a metallic element, intended to stabilize the structure and fine-tune the properties to a specific application or environment [3].

Both coating families may be called *triboactive*, meaning that they in a tribological contact spontaneously form and maintain a low-friction layer in the interface. This interfacial layer, or *tribofilm*, is often formed from a mixture of the original contacting materials and elements from the environment, such as oxygen, water, or lubricant additives. Tribofilms associated to the DLC and TMD families typically show a lamellar structure, where internally strongly bonded atomic planes