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New understanding of the initiation of material transfer and transfer layer build-up in metal forming—In situ studies in the SEM

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ABSTRACT

The tribological mechanisms behind the initiation of material transfer and build-up of transfer layers in aluminium forming have been studied in situ in the SEM where a tip of aluminium is put into contact with a tool steel surface under controlled sliding contact conditions.

By combining in situ observations with post-test high resolution FEG-SEM studies of the contacting surfaces we have shown that aluminium is immediately transferred onto the fine polished tool steel. It was also confirmed that the initial transfer occurs on a very fine scale and is localised to the surface irregularities presented by the slightly protruding carbonitrides. In contrast, the less protruding M_6C carbides, as well as the martensitic steel matrix exhibit very little initial transfer.

Intentionally made scratches (roughly 5 μm wide and 2 μm deep) across the tool surface immediately result in larger scale transfer, which grows upon further passages of work material causing a high coefficient of friction. The study illuminates the extreme value of combining the in situ technique with high-resolution scanning electron microscopy using low acceleration voltage as a mean to detect the very thin initial transfer layers. With the higher acceleration voltages normally used, the transferred aluminium becomes transparent and can hardly be detected.

1. Introduction

High friction and transfer of work material to tool surfaces constitute important industrial problems in cold forming of aluminium. The high friction results in high forming forces that limit the forming possibilities; for example the cavities of dies will not be completely filled when the shapes get too complex or their radii small. The transferred work material results in increased friction forces when forming the following piece and also impairs its surface finish. Thick and uneven transferred material will result in scratches and other types of imperfections on the surface formed. This process is commonly called galling.

The area has been researched for many years, and the forming processes (tool materials, coatings, surface preparation processes, lubricants, etc.) have gradually been developed so that today more advanced shapes and more units can be formed before the tool must be exchanged or reconditioned [1–6].

The transfer of aluminium to harder (tool) surfaces and its influence on friction has been investigated using several approaches. Despite the extensive research, there is still a lack of understanding of the physical and chemical mechanisms involved. Typically, the investigations have not been capable of giving detailed information of the decisive mechanisms and the initiation of transfer, or capable of detecting very thin transfer layers. Usually, the very initial stages of transfer have not been studied at all. Rather, the surfaces have been investigated first when a lot of material has been transferred, and therefore covered any signs of where it originated. Furthermore, the evaluation techniques or the instrument settings selected have typically not allowed detection of thin transfer layers [7–9].

It has proven difficult to gain a deeper understanding of these phenomena by studying real forming operations. It is very hard to control and measure the different parameters, the tests are expensive and time consuming and the sizes of the tools and work material pieces make them less suitable for in depth microscopy studies and surface analysis. It is also impossible or very awkward to repeatedly interrupt the processes to study the effect of individual forming events, or after very short sliding distances, etc. Although instrumental in the evaluation of new materials, coatings, finishing operations and lubricants, many of the simplified laboratory tests developed have shown limitations when it comes to investigate the fundamental mechanisms of transfer.

Typically, these laboratory tests involve some scaled down contact between a hard tool material and the softer work material, under a contact pressure that leads to plastic deformation of the

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work materials. Although the deformation takes place at a smaller scale and in a simpler geometry than actual forming operations, the initiation of material transfer is frequently hidden and cannot be directly observed. Further, even if the process is interrupted and the surfaces are studied in a microscope, the transferred material often grows and covers a relatively large area making it hard to identify the point of initiation. The nominal contact area is typically much larger than the individual transfer events, which makes it hard to correlate the registered friction curve with the transfer events. By post test examination in the scanning electron microscope (SEM), it has several times been shown that if the tool surfaces are rough, this increases the amount of transfer, and the transferred material is localised to the grinding marks and other surface defects. For well-polished surfaces, the initiation of transfer is less straightforward to establish. It has proven very demanding to decide

- whether the resulting surface appearance is due to a steadily growing amount of transfer or if the process has involved repeated transfer and removal,
- whether the observed sizes and thicknesses of transferred material is due to individual occurrences or resulting from accumulated growth,
- whether areas not showing transfer is due to never having been in contact, never have caused transfer or have had transferred material which has then been removed,
- the relationship between the observed transfer and the initiating mechanisms (is it due to micro roughness, damage of tool surface, chemical bonding to specific phase in the tool material, etc.).

First-principles calculations have been used as an alternative approach to investigate how the chemical bonding may affect the adhesion and subsequent transfer tendency. This type of simulation is very direct and does not involve coarse approximations on the atomic scale, but on the other hand requires that the mating surface materials are strongly simplified. The number of atoms involved must be small, and the simulations therefore cannot include large-scale phenomena such as roughness. The bonding state and strength of individual atoms within well-defined pieces of two materials (crystalline orientation defined, no oxidation, no plastic deformation, etc.) and over the well-defined interface between them (atomically clean, relative orientation and sliding direction predefined, etc.) is estimated based on density functional theory. Despite these simplifications of real tribological situations, interesting results have been presented, and the approach has shown great potential.

Vitos et al. [10] addressed the difference in transfer and galling behaviour observed between titanium nitride and vanadium nitride coated surfaces slid against steels. It was experimentally found that VN exhibits lower friction and better galling characteristics than the TiN coating. Using first principles simulations, they present an insight to the atomic level processes initiating galling at TiN-Fe and VN-Fe interfaces, respectively. They conclude that the difference in sticking and sliding properties between VN and TiN on Fe originates from the different potential energy surface roughness of these materials. They claim that their findings indicate that when designing for anti-galling surfaces, besides the well-known surface roughness, one should also consider the atomic-level roughness as a key design parameter. While the polishing operation controls the micro-scale roughness, the atomic-level roughness has a pure quantum mechanical origin and can only be controlled by the chemical composition.

In a recent paper, the transfer of aluminium to fluorinated diamond like carbon surfaces (F-DLC) was studied by Sen et al. [11]. The atomic interactions at the Al/diamond:F interfaces were studied and compared to those of Al against hydrogenated DLC (H-DLC). The predictions of these calculations were analysed and compared with sliding contact experiments, and provided insight into the mechanisms of the material transfer and friction behaviour of these coatings. Their main results included predictions that F atoms would transfer to the Al when the contact pressure at the interface reached 3.5 GPa. Higher contact pressures yielded more F transfer to Al. No corresponding transfer of H occurred from a diamond:H surface to Al when they were pressed together. The bond structure at the F-transferred Al surface predicted the formation of a stable AlF_3 compound, which was also experimentally confirmed by XPS and FIB HRTEM. Experimentally, H-DLC coatings in sliding contact against Al generated an initially high friction due to wear and plastic deformation of the Al counterface. Once a carbonaceous transfer layer passivated by–H and–OH was established, a low steady-state $\mu \approx 0.20$ was attained. After a similar process the F-DLC coatings showed a 30% lower friction ($\mu = 0.14$) as a consequence of F transfer to carbon layers and the resulting repulsion between the two F-passivated carbon surfaces.

Despite the different types of investigations conducted, several important questions remain unanswered:

- Where is the transfer initiated on well-polished tools?
- What is the role of the oxide on the aluminium material? The native oxide is some 20 times harder than the underlying metal [12], but it is extremely thin (only 2–3 nm).
- What is the role of chemical bonds between the two surfaces in relation to the mechanical scraping due to roughness?

In this paper we have gained new fundamental understanding by performing carefully designed in situ tests in the SEM. The in situ manipulator was first designed and used for micro scale scratch testing and fundamental abrasion studies [13–15]. The present tests used the same general set up, but adopted to forming. It was designed to avoid as much as possible of the complexity of real forming while preserving fundamental elements of the contact situation in forming, i.e. sliding contact between a tool surface and a work material, under pressure sufficient to cause substantial plastic deformation of the work material. As in ordinary forming, this is a one way material transfer situation, meaning that virtually no tool material is transferred to the work material surface.

The experimental approach allows direct observation of deformation and material transfer between a well-defined tool material surface and a needle shaped work material tip in the SEM, and all events observed can be directly correlated to the continuously recorded friction curve. The studies also include subsequent high-resolution SEM investigations of both contacting surfaces to further characterise the initiation of material transfer and transfer layer build-up.

One tool material was tested, representing leading commercial qualities of powder metallurgical cold forming tool steels. The material was tested in two surface conditions; well-polished, and well-polished with local intentional scratches, representing worse polishing or a damaged tool surface.

2. Experimental

The initial conditions and material transfer in a forming operation have been studied in a contact situation where the work material has been represented by a relatively sharp tip that has been slid against a flat tool material under such load that the softer work material has deformed plastically. The contact area becomes very limited, initially determined by the load and the