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Tribological performance of Ni-based self-lubricating claddings for high temperature forming of lightweight alloys

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Abstract

The aim of the present research work was to investigate tribological performance and potential of Ni-based self-lubricating claddings for high temperature forming of lightweight alloys. Laser claddings included in this investigation were based on Ni-matrix with the incorporation of 5 wt% silver and 10 wt% MoS2 as solid lubricant precursors. Tribological evaluation and testing was performed by Load-Scanner to simulate hot forming process and results compared to high performance hot work tool steel. To simulate hot forming process of forging, wire drawing and extrusion, tests were done at room and elevated temperatures (150°C and 300°C) against typical light-weight alloys, including AISI 316L stainless steel, 6xxx series Al alloy and Ti6Al4V Ti alloy and results evaluated in terms of coefficient of friction vs. load, critical loads for galling initiation and volume of adhered work material. Results show that self-lubricated claddings with incorporated MoS2 and Ag as solid lubricants in general provide lower and more stable friction as well as improved galling resistance in high temperature forming of lightweight alloys. Positive effect of self-lubricating claddings intensifies with forming temperature, degree of plastic deformation and work material tendency to galling.

Introduction

Hot forming, especially hot forming of lightweight alloys, is a very demanding operation requiring tool material with high strength and toughness, oxidation and wear resistance, but above all good anti-galling resistance. High operating temperatures are associated with detrimental mechanisms like oxidation, thermal softening, loss of strength and poor wear resistance. Furthermore, material transfer between the contacting counterparts by adhesive wear (galling) is usually intensified by temperature, which affect both, tool lifetime and the quality of the finished products [1]. Thus, in high-temperature forming galling is a major cause of high and unstable friction, poor surface quality of the produced parts and production downtime. To mitigate these challenges high-performance hot work tool steels are used, often combined with protective coatings. Furthermore, due to high affinity to galling and to prevent excessive material transfer forming of lightweight alloys has to be performed under lubricated conditions [2].

While forming at high operating temperatures brings conventional tool steels to their limits, the use of conventional liquid lubricants is impractical due to required cleaning steps or even not possible as oils and greases degrade quickly at temperatures above 200°C [3]. On the other hand, PVD coatings although very successfully used in cutting and simple cold forming applications have deposition limitations, with typical hard coatings like TiN, AlCrN, TiAlN showing a significant degree of material transfer when tested against lightweight alloys at high temperatures, thus greatly limiting their implementation in the real field application [4]. In order to overcome these limitations, new lubrication approaches effective at high temperatures have become the subject of great interest in recent years. In this context, solid lubricants like graphite, hBN or MoS_2 are preferred and readily implemented in practice [5], although they have been reported to provide insufficient lubrication during hot forming of light metals [6]. In recent years, a new approach for effective lubrication at high temperatures based on the incorporation of solid lubricants to both coatings and bulk materials has been investigated, showing a great potential for decreased friction and wear at high temperatures [7]. Especially nickel-based laser claddings with the addition of silver and transition metal dichalcogenides have been found as promising candidates for hot forming operations, i.e. hot stamping of ultra-high strength steels, showing a significant decrease of friction and adhesive wear up to temperatures of 600°C [8].

The aim of the present research work was to investigate tribological and anti-galling performance, and potential of nickel-based self-lubricating laser claddings for high temperature forming of demanding lightweight alloys. It is expected that the use of self-lubricating claddings on the forming tool will increase the stability of the friction process, reduce material transfer, and eliminate or at least reduce the need for added lubricant.

Materials and Experimental Methods

In the present study, a nickel-matrix based laser cladding with the incorporation of 5 wt% silver and 10 wt% MoS_2 as solid lubricant precursors was deposited on several AISI 304 stainless steel cylinders of diameter 10 mm and a length of 100 mm. AISI 304 stainless steel was chosen as a substrate material due to its high high-temperature oxidation resistance, thus preventing the formation of scale during laser cladding. The incorporation of 5 wt% Ag and 10 wt% MoS_2 was considered to be optimum in terms of the microstructure of the resulting claddings, resulting in an excellent performance under hot hardness and high-temperature oxidation tests as detailed in previous publication [9]. Cladding deposition was performed by a direct diode laser with a wavelength of 975 nm, as this technique allows for a single-pass melting of the precursor material avoiding the re-melting of the resulting claddings. A NiCrSiB commercial powder with a chemical composition consisting of 0.2% C, 4% Cr, 1% B, 2.5% Si, < 2% Fe, 1% Al and balance Ni (in wt%), and a particle size between 50 and 150 µm was used. Ag and MoS_2 powders used as solid lubricant had a maximum particle size of 45 µm and 75 µm, respectively. The base NiCrSiB powder and the solid lubricants were mechanically mixed using ethanol as binder, spread over a stainless-steel cylinder and dried in an oven at 100°C for 1h. Prior to the deposition, a sandblasting step with silica sand was performed in order to improve the adhesion of the resulting claddings. The final step was laser cladding under an argon protective atmosphere, performed by using a rectangular shaped beam, beam speed of 10 mm/s and beam power density of 85 W/mm^2. The as-deposited hardness of the cladding was measured to be 400 HV10. Additional characterization of the chosen cladding by means of microstructure and XRD can be found in Ref. [9].

As a reference material, the hardened high performance hot work tool steel QRO 90 Supreme from Uddeholm was used. The tool steel has the following chemical composition (in wt.%): 0.38% C, 0.3% Si, 0.8% Mn, 2.6% Cr, 2.3% Mo, 0.9% V, balance Fe and was hardened following the recommended heat treatment procedure by the steel producer to a hardness of 540 HV10. As the counter body material, three lightweight alloys were selected, including AISI 316L stainless steel in solution treated condition (270 HV10), AA6082 aluminium alloy in T6 condition (115 HV10) and commercial Ti6Al4V titanium alloy (300 HV10). All counter materials were machined into ϕ10 x 100 mm cylinders, and ground and polished to an average surface roughness of R_a = 0,2 µm.

To simulate hot forming process of forging, wire drawing and extrusion, the tribological testing was performed on a high temperature tribometer with a load-scanner configuration (Fig. 1). This test rig is described in detail in Ref. [10]. Load-scanner configuration utilizes cross-cylinder contact geometry where normal load is gradually increased during sliding with each point along the contact corresponding to a specific load without any loading history. This configuration provides information on the coefficient of friction vs. load and allows determination of critical loads for galling initiation and transfer layer build up. The major benefit of this equipment is that the single-pass configuration features a continuous contact with fresh sample surface and is thus more representative of metal forming processes than typical reciprocating or sliding pin-on-disc tribometers [10]. The investigations were performed at a sliding speed of 0.01 m/s and at room (RT) and high temperature (HT; 150°C & 300°C), chosen based on the typical temperatures for hot forming of lightweight alloys. The applied load was increased during the single-pass tests along the distance of 85 mm from 200 N to 1400 N for RT tests and from 50 to 450 N for HT tests, corresponding to a substantial plastic deformation. Results were evaluated in terms of coefficient of friction vs. load, critical loads for galling initiation, volume of adhered material and wear track surface analysis.

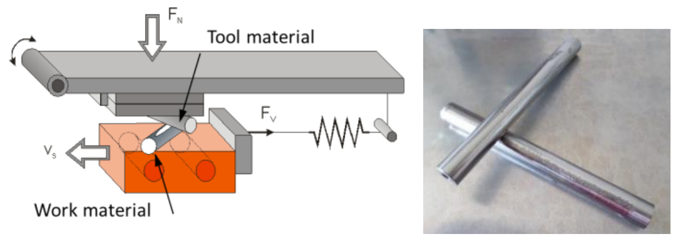

Figure 1: Load-scanner test configuration.

Prior to testing reference tool steel and cladded cylindrical specimens were ground and polished (R_a = 0.1 µm), cleaned with ethanol and dried in air. Due to the severity of high temperature forming of lightweight alloys and proven necessity of using external solid lubricants even in the case of self-lubricating claddings [11], a thin layer of commercial MoS_2-based solid lubricant was applied on the surface of self-lubricating cladding and the reference tool steel prior to testing. The as-delivered solid lubricant was mixed with demineralized water in 15:85 ratio and sprayed on the chosen samples pre-heated in furnace to 130°C.

Results and Discussion

Stainless steel

Results for room temperature tests and AISI 316L stainless steel are presented in Fig. 2. As compared to uncoated tool steel (QRO), self-lubricating cladding (CLAD) provides about 40% lower and more stable friction (Fig. 2a), and 20% higher critical loads for galling initiation and transfer layer build up, as indicated by sudden friction increase and coefficient of friction becoming unstable, respectively. This is further confirmed by the amount of transferred work material adhered to the "tool" material, being more than 50% lower in the case of self-lubricating cladding, with the beneficial effect of self-lubricating cladding being intensified with load and degree of plastic deformation, as shown in Fig. 2b.

At elevated temperature of 150°C, self-lubricating cladding doesn't provide any evidential improvement compared to conventional tool steel in terms of level and stability of coefficient of friction, as shown in Fig. 3a. However, it results in 20 – 40% better galling resistance (Fig. 3b).

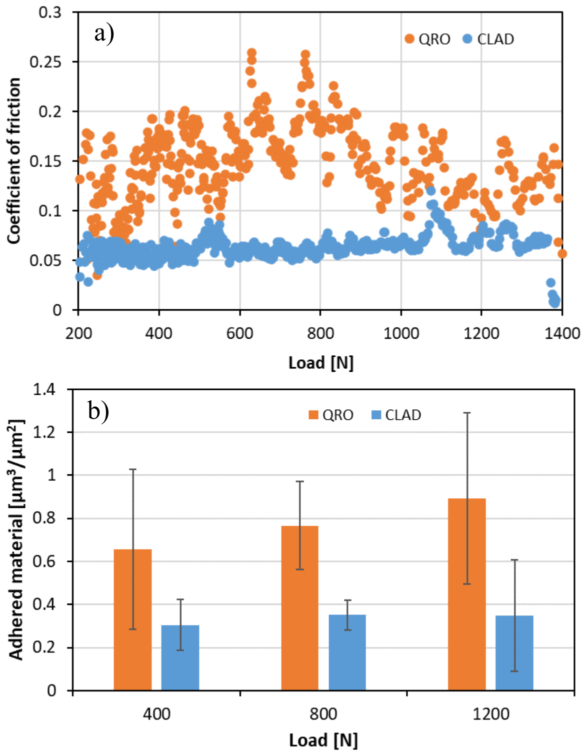

Figure 2: (a) Coefficient of friction and volume of adhered work material for RT tests against AISI 316L stainless steel.

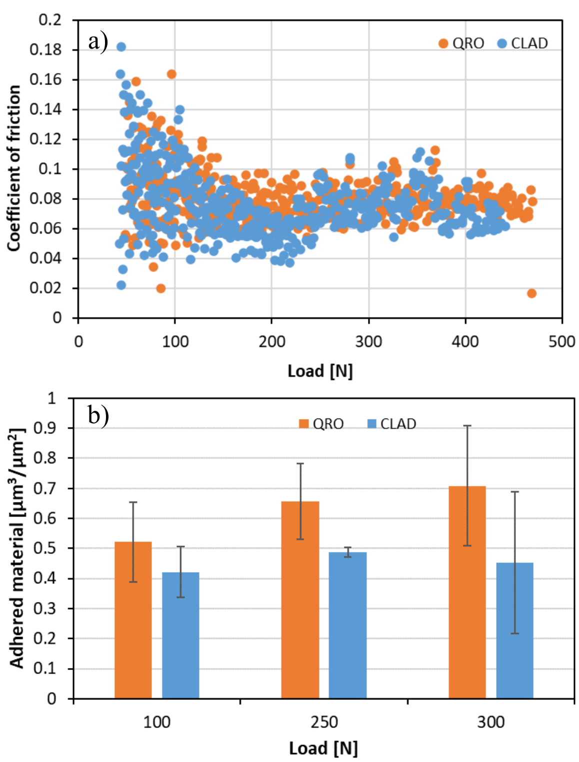

Figure 3: (a) Coefficient of friction and volume of adhered work material for HT tests (150°C) against AISI 316L stainless steel.

Al alloy

Similar results were observed also in the case of AA6082 alloy. At RT self-lubricating cladding provides about 20% lower, but much more stable friction than uncoated tool steel. Critical loads for unstable friction were increased by the factor of 2, however, the amount of adhered material remained more or less the same. Contrary, at elevated temperatures of 300°C self-lubricating cladding provided 30-40% lower friction (Fig. 4a) as well as improved galling resistance, although positive effect diminishes at high loads, as shown in Fig. 4b.

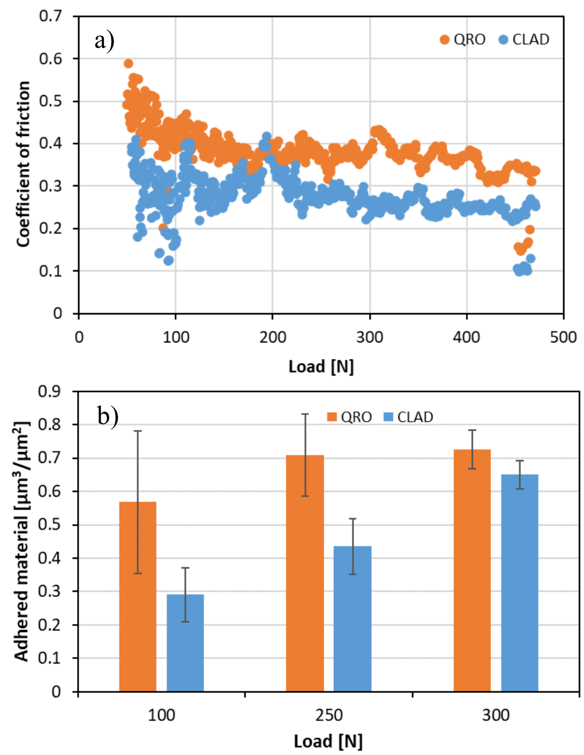

Figure 4: (a) Coefficient of friction and volume of adhered work material for HT tests (300°C) against AA6082 alloy.

Improved galling performance provided by the application of self-lubricating cladding was further confirmed by multi-pass tests at elevated temperatures, clearly showing more moderate friction increase as the number of cycles and load are intensified (Fig. 5).

Better galling resistance provided by self-lubricating cladding is directly related to the presence of lubricating compounds, as CrS and MoS_2, which prevent adhesion of work material to the “tool” surface, as shown in Figs. 6 and 7.

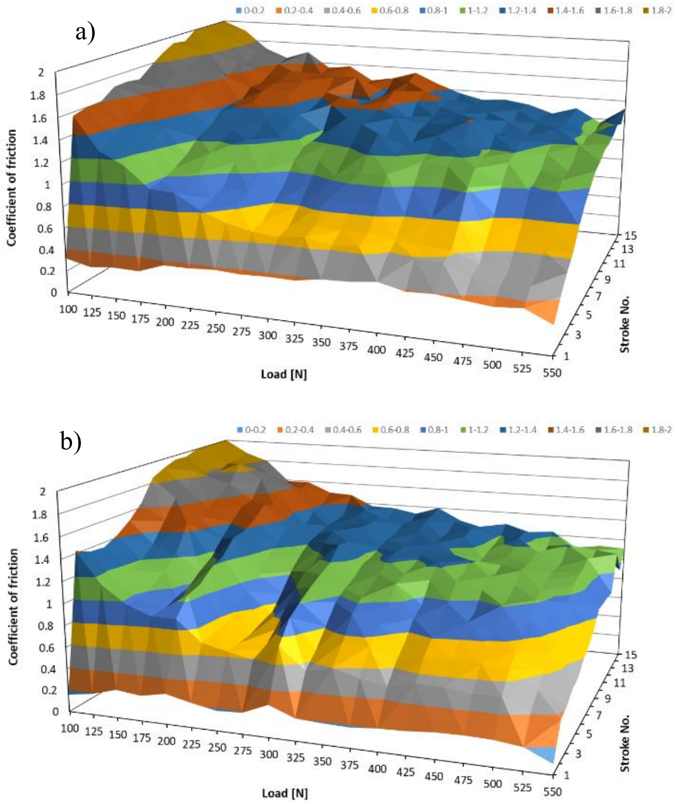

Figure 5: Friction maps for HT tests (300°C) against AA6082 alloy; a) tool steel, b) self-lubricating cladding.

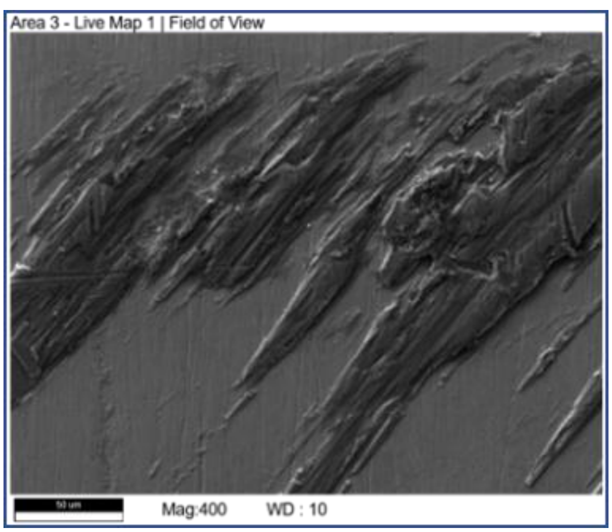

Figure 6a: Tool steel wear track for HT test (300°C) against AA6082 alloy.

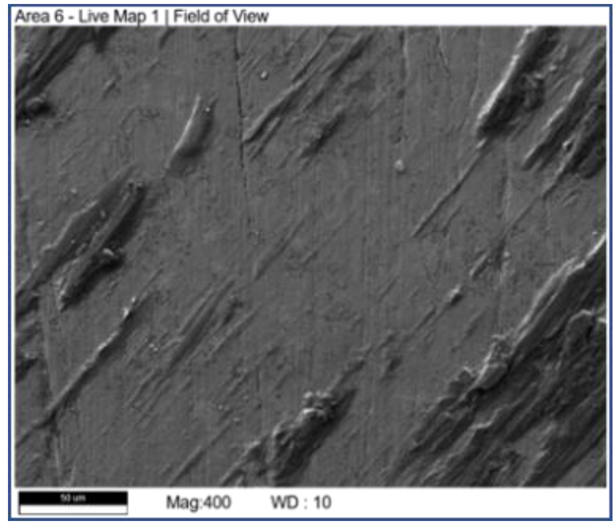

Figure 6b: Self-lubricating cladding wear track for HT test (300°C) against AA6082 alloy.

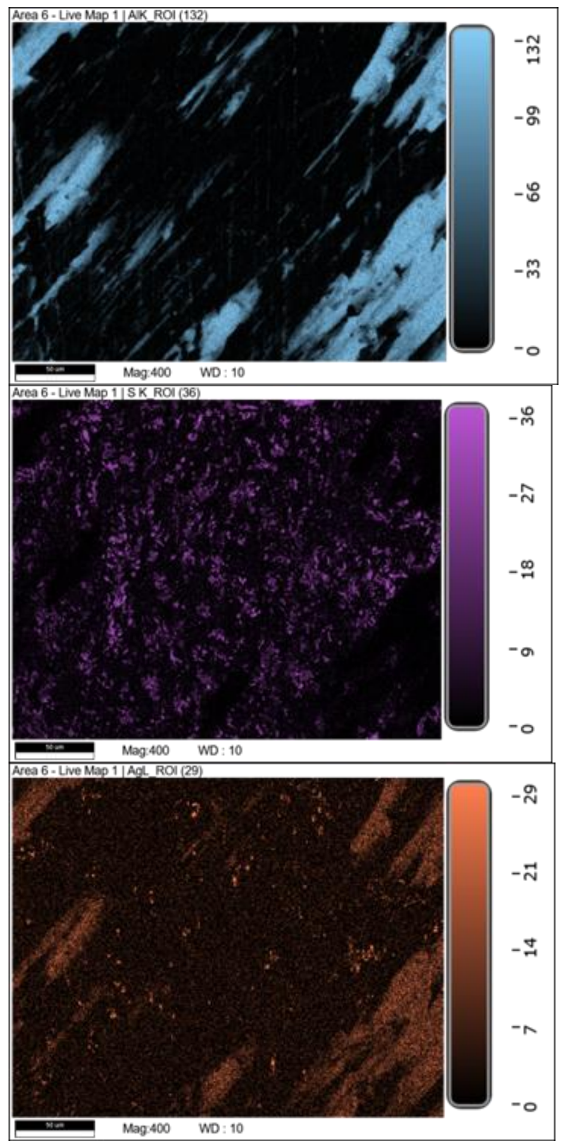

Figure 7: EDS maps (Al, S, Ag) of self-lubricating cladding wear track after HT tests (300°C) against AA6082 alloy (800 N).

Ti alloy

Contrary to stainless steel and Al alloy, testing against Ti6Al4V alloy resulted in about 20% higher friction when using self-lubricating claddings (Figs. 8a and 9a). However, as compared to uncoated tool steel, self-lubricating claddings provide more stable friction in wider load range, higher critical loads for galling initiation and greatly reduced volume of adhered work material, especially for high temperature testing, as shown in Figs. 8b and 9b.

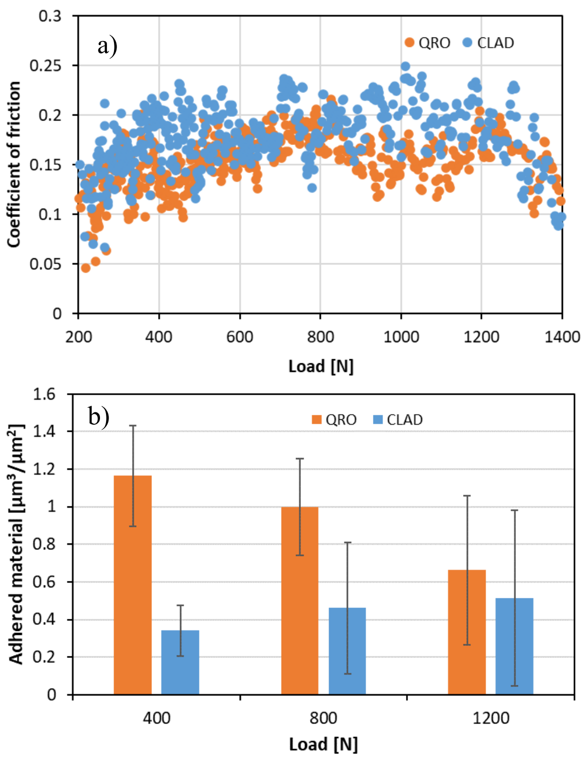

Figure 8: (a) Coefficient of friction and volume of adhered work material for RT tests against Ti6Al4V alloy.

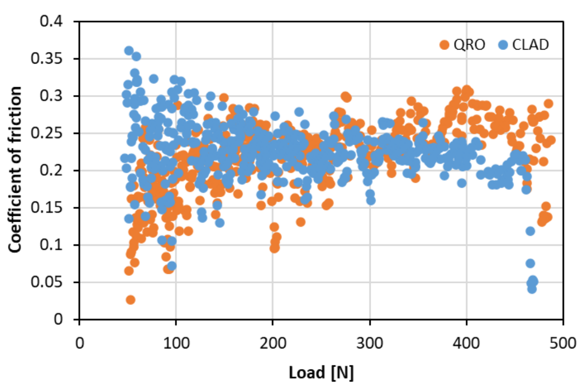

Figure 9a: Coefficient of friction for HT tests (300°C) against Ti6Al4V alloy.

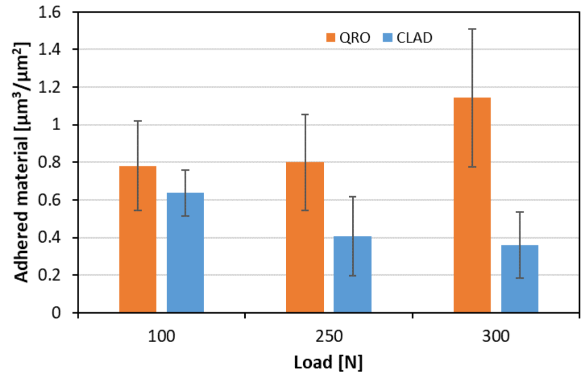

Figure 9b: Volume of adhered work material for HT tests (300°C) against Ti6Al4V alloy.

Conclusions

- Self-lubricated claddings with incorporated MoS_2 and Ag as solid lubricants generally provide lower and more stable friction in high temperature forming of lightweight alloys, obtained through the localized supply of lubricious substances released due to high contact temperatures and loads.
- Islands of solid lubricant prevent direct contact between the tool surface and the work material, resulting in increased critical loads for galling initiation and transfer layer build-up as well as substantially reduced volume of adhered work material. Positive effect of self-lubricating claddings intensifies with forming temperature, degree of plastic deformation and work material tendency to galling.
- In the case of stainless steel improved tribological performance is mainly related to room temperature conditions. For Al alloy self-lubricating claddings provide more stable friction at room and elevated temperature while improved galling resistance is limited to high temperatures. Although in the case of Ti alloy friction in general increases with the application of self-lubricating claddings, it is much more stable and galling resistance substantially improved in a wide temperature and load range.

Acknowledgments

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