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Self-lubricating laser claddings for reducing friction and wear from room temperature to 600 °C

H. Torres[a,b,*], T. Vuchkov[b], S. Slawik[c], C. Gachot[d], B. Prakash[b], M. Rodríguez Ripoll[a]

[a] AC2T research GmbH, Viktor-Kaplan-Straße 2/C, 2700 Wiener Neustadt, Austria
[b] Luleå University of Technology, Department of Engineering Sciences and Mathematics, 971 87 Luleå, Sweden
[c] Saarland University, Department of Materials Science and Engineering, 66123 Saarbrücken, Germany
[d] Technische Universität Wien, Department of Engineering Design and Logistics Engineering, Vienna, Austria

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ABSTRACT

In this work, laser cladding has been employed for the preparation of nickel-based self-lubricating coatings featuring the addition of different combinations of soft metal solid lubricants such as Ag and Cu. Transition metal dichalcogenides (WS_2, MoS_2) were evaluated as precursors for encapsulating and uniformly distributing the soft metals throughout the microstructure. The tribological behaviour of the resulting claddings was evaluated under high temperature reciprocating sliding conditions, including two different counter body geometries that lead to very different ranges of contact pressures during testing. An improved tribological behaviour was observed for the self-lubricating claddings compared to the unmodified nickel-based alloy up to 600 °C, attributed to the presence of silver and the formation of lubricous sulfides during sample preparation due to the thermal degradation of the transition metal dichalcogenides precursors. Additionally, the role of the contact conditions observed when testing the self-lubricating claddings against flat pins instead of spherical counter bodies are discussed in terms of frictional and wear microstructural mechanisms.

1. Introduction

Laser cladding can be effectively used for the deposition of protective coatings for reducing wear in a wide range of industrial applications including ore processing, steel making and aerospace [1–3]. In addition to the good quality of the deposited coatings [4] and their excellent metallurgical bonding to the substrate [5], this technique also allows for the repair and refurbishing of damaged, high-value components like turbine blades which otherwise would have to be replaced. The fundamentals of the cladding process involve the use of a laser beam for the melting of a precursor material, generally used in powder form. The controlled heat input allows for a small heat affected zone (HAZ) in the substrate [6,7], thus leaving the mechanical properties of the underlying material unaffected. The precipitation of metastable hard phases in the cladding is also an interesting feature of this technique [8], as it can lead to improved resistance to damage mechanisms such as abrasion or corrosion.

In recent years there has been a growing interest in self-lubricating materials capable of operating at high temperature (HT), as oils and greases are no longer an option above temperatures of 350 °C [9]. Within this context, nickel-based alloys have attracted a good deal of interest as the base material for the preparation of laser claddings suited for high temperature applications [10–12]. The subsequent addition of solid lubricants has led to the development of nickel-based self-lubricating laser claddings showing good performance at HT, as it is well attested in the available literature [13–16]. Among these added solid lubricants, silver is widely reported [17] due to its high thermal conductivity and low toxicity, making it well suited for its incorporation in self-lubricating composites and coatings, as shown by in the available literature [9,18–21].

Transition metal dichalcogenides (TMDs) like MoS_2 and WS_2 have been widely referenced in the available literature dealing with self-lubricating materials [22–24], although they have also been observed to thermally decompose during laser cladding due to the very high temperatures involved in the melting process, despite the use of a protective atmosphere to prevent oxidation [13,25]. However, previous studies [16,26] have shown the feasibility of using MoS_2 in combination with silver as dopants in nickel-based self-lubricating laser claddings. The observed microencapsulation of silver inclusions surrounded by a sulfide phase led to a uniform distribution of solid lubricants throughout the entire width of the resulting laser claddings, a mechanism which was regarded to be beneficial in terms of the resulting microstructure and the tribological properties of the claddings.

The available literature also points to other constituents as potential

* Corresponding author at: AC2T research GmbH, Viktor-Kaplan-Straße 2/C, 2700 Wiener Neustadt, Austria.
E-mail address: torres@ac2t.at (H. Torres).

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additions to HT self-lubricating materials. Copper, a soft metal like silver, has been the subject of some research due to interesting properties like its high thermal conductivity, which could help reduce frictional heating during sliding and could be also important in applications like hot stamping. However, most if not all of the available references dealing with pure copper involve tribotesting at room temperature (RT), less representative for applications like metal forming. Additionally, a TMD like WS_2 has been reported to be an effective HT solid lubricant [13], with a thermal stability higher than that of MoS_2 (WS_2 oxidises at ~540 °C, in contrast to the 370–480 °C interval reported for the latter [27,28]), although having a higher density and being on the other hand significantly more expensive than its molybdenum-based counterpart. However, it must be noted here that no systematic comparison of the HT tribological behaviour of WS_2 and MoS_2 has been found in the available literature. Additionally, the available literature studying the HT tribological behaviour of self-lubricating laser claddings is sparse [9], despite of the favourable properties which can be achieved for the resulting coatings.

In order to shed further light into the HT tribological behaviour of potential solid lubricant dopants like the ones previously discussed for laser claddings, nickel-based self-lubricating coatings were prepared with the incorporation of soft metals like silver and copper in addition to TMDs precursors like MoS_2 and WS_2. The claddings were subsequently evaluated at HT under conditions representative of those found in metal forming. Steel-based counter bodies with different geometries (bearing balls and flat pins) were chosen for testing. It must be noted, however, that in the available literature concerning self-lubricating materials, the use of ceramic ball counter bodies is still prevalent.

Additionally, during the present study the role of different TMDs like MoS_2 and WS_2 on the resulting microstructure and HT properties of the laser claddings will be studied in detail, as this issue has been insufficiently addressed in the available literature. Additionally, the effectiveness of copper as a cheaper substitute of silver in sliding applications will also be assessed.

2. Experimental

2.1. Materials preparation

The preparation of the self-lubricating claddings was performed using a direct diode laser, due to the low defect density of the resulting coatings in addition to their excellent metallurgical bonding with the substrate. This technique features also a higher efficiency than other types of laser-based deposition [29] and allows for the single-pass melting of the precursor material, preventing the detrimental remelting of the claddings. The base material was a NiCrSiB commercial powder supplied by Castolin Eutectic, with a chemical composition in wt% of 0.2 C, 4 Cr, 1 B, 2.5 Si, < 2 Fe and 1 Al. Boron and silicon additions decreased the melting point of the mixed powder, being beneficial for the deposition of this nickel-based self-fluxing alloy [30], while the chromium content contributed to decrease oxidation at HT.

Ag powders to be used as solid lubricants were purchased from Goodfellow, with a maximum particle size of 45 μm. Copper powder was procured from Oerlikon Metco, with a particle size up to 90 μm. MoS_2 was provided by Tribotecc GmbH with a particle size ranging from 5 to 75 μm, while WS_2 delivered by Goodfellow had a particle size smaller than 10 μm. The chemical compositions for all of the coatings prepared in this study are listed in detail in Table 1, including an unmodified NiCrSiB cladding used as the reference material. The coatings used for this study were deposited on grade 1.4301 stainless steel plates to prevent scale formation during laser cladding and HT tribotesting. For the present study, the maximum dilution of the prepared claddings was 10.7%.

Table 1
Solid lubricant content for the deposited coatings. Results for the reference alloy, 10 MoS_2 and 5 Ag – 10 MoS_2 were taken from [26].

Claddings	Solid lubricant content (wt%)				Roughness Ra [μm]	RT hardness [HV1]
	Ag	Cu	MoS_2	WS_2		
Reference	0	0	0	0	0.09 ± 0.03	356 ± 11
10 MoS_2	0	0	10	0	0.10 ± 0.02	392 ± 15
5 Ag – 10 MoS_2	5	0	10	0	0.10 ± 0.03	398 ± 5
10 WS_2	0	0	0	10	0.15 ± 0.06	391 ± 5
5 Ag – 10 WS_2	5	0	0	10	0.15 ± 0.02	394 ± 8
10 Cu – 10 MoS_2	0	10	10	0	0.11 ± 0.01	359 ± 6

2.2. High temperature reciprocating sliding tests

The tribological behaviour at HT of the laser claddings was studied using an Optimol SRV friction and wear tester, as described in [26]. The upper counter body samples were made of AISI 52100 steel as it was readily available in the form of spherical balls and cylindrical bearings. The AISI 52100 steel represents in our case the workpiece in a typical forming process. The steel samples were loaded against a stationary hardfacing sample by means of a spring deflection mechanism and oscillated by means of an electromagnetic drive while the lower flat sample representing the tool was heated resistively up to nominal temperatures of 800 °C. Actual temperatures on the sample surface were measured using a thermocouple prior to test start. The preparation of the cladding samples consisted of a machining step to a size of 12.6 × 12.6 × 4.7 mm^3 followed by a manual grinding with grit 360 and grit 600 SiC-abrasive paper, rotating the samples during the last step to remove any directionality or lay in the resulting sample surface. Roughness R_a prior to testing was measured using a New ViewTM 7300 3D optical profiler and was found to lie between 0.1 and 0.2 μm for all of the chosen claddings. All specimens were ultrasonically cleaned in petroleum ether prior and after testing and rinsed with acetone.

The reciprocating frequency and stroke length were chosen so that the average sliding speed for all of the tests was 0.1 m/s, within the range reported for metal forming applications [31–33]. Three repetitions were performed at least for each condition, in order to ensure repeatability. The following counter body configurations, leading to different contact geometries and pressure ranges during testing, were chosen:

2.2.1. Ball-on-flat

For this series of tests, commercial AISI 52100 bearing balls with a diameter of 10 mm were used as the counter bodies. The applied normal load was set to 50 N as it was observed to lead to more stable tribological behaviour during preliminary testing. The maximum Hertzian contact pressures during testing were calculated to be 1691 MPa. The chosen parameters for ball-on-flat tests are summarised in Table 2.

2.2.2. Flat pin-on-flat

In this case, flat pins with a diameter of 2 mm were manufactured from commercial AISI 52100 needle rollers, with the resulting edges being manually ground with grit 600 sandpaper to reduce the onset of

Table 2
Test parameters chosen for the HT reciprocating tests against AISI 52100 bearing balls.

Test parameters	Reciprocating ball-on-flat
Load [N]	50
Sample temperature [°C]	RT, 150, 300, 400, 600
Stroke length [mm]	2
Frequency [Hz]	25
Duration [s]	900