Cladded steel for clutch disc carriers

On the formability and wear properties

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Abstract
Current clutch disc carriers are often heat treated in complex ways to provide for the required wear resistance. Using steels cladded by hot rolling could be a cost efficient alternative. However, such cladded steels need to simultaneously show high wear resistance as well as good formability to ensure the manufacturability of the disc carrier. In the present work the wear resistance of a low-alloy steel cladded with a thin 100Cr6 layer is characterized using a pin-plate test. To evaluate the formability bending tests are conducted. It is found that the wear resistance of the cladded steel is superior to that of the monolithic high-strength low-alloy steel. The formability of the cladded steel is found to be good in general, however, inferior to that of the monolithic steel.

1 Introduction

Current clutches have to transmit very high torque, concurrently installation space steadily decreases. This leads to highest geometrical complexity of clutch disc carriers and, thus, higher contact pressure on the tooth surface. Accordingly, good formability of the material to be employed (to enable the producibility) as well as high wear resistance are required simultaneously. Unfortunately, these two properties usually contradict each other. In current industrial practice this issue is solved by using a highly ductile, micro-alloyed steel, combined with a suitable heat treatment after the forming process. Due to the superior resulting wear resistance, plasmanitrocarburization (PNC) often is chosen as the most suitable heat treatment [1]. Unfortunately, the PNC process is very costly as well as causing warpage of the component and, thus, a high demand for establishing an alternative processing route prevails.
With the recently developed new cladding process by thyssenkrupp Hohenlimburg GmbH, cladded steel sheets with defined, functionally graded properties are available for large scale production [2, 3]. The robust, large scale industrial processability of these materials is the key for the application of layered materials in the automotive industry due to the high volumes and constant high quality being required. Since cladded steels are thought to be characterized by high ductility and high wear resistance simultaneously, they are promising candidates for the clutch disc carriers to omit the otherwise needed heat treatment.

For cladding of steels (in order to increase the wear resistance) techniques like laser cladding or chemical vapor deposition were employed numerously and investigated in detail, e.g. in [4]. The application of cladded steel sheets as starting material for parts subjected to tribological loading is rarely mentioned in literature [5], and was not investigated in detail, yet. Current research focusing on steels cladded by rolling mainly comprises multilayered steel composites characterized by superior mechanical properties required for lightweight structural applications [6–8], e.g. for pillars or other similar components. Most of these composites feature internal hard layers cladded by ductile layers on both sides to enhance the formability by suppressing necking [7]. Cladded structures for wear resistant application, however, require the hard layer to be on the outside. Furthermore, the volume fraction of the different alloys used for realization of the steel composites investigated in most studies available in open literature usually is equal or at least similar, i.e. layers cladded are relatively thick [6, 7, 9]. For wear resistant applications, a very thin clad would already be sufficient. In consequence, the formability of the latter has to be analyzed carefully as due to the different design of the investigated cladded steels characterized so far and those designed for wear resistant applications findings being available cannot be transferred straightforward.

The present study has been conducted to provide for first steps towards the envisaged, challenging application. To close currently prevailing research gaps, a micro-alloyed steel sheet cladded by hot rolling with a 100 µm thick 100Cr6 clad. The CS was analysed after annealing. To obtain values for both, the clad and the base layer, OES was conducted on both sides of the CS sheet.

To analyze the microstructure optical microscopy was employed. The specimens were prepared utilizing standard polishing technics and were etched with 3% alcoholic nitric acid.

The mechanical properties were characterized by tensile testing using a Zwick/Roell Z250. The crosshead speed was set according to DIN EN ISO 6892-1, i.e. stress controlled within the elastic region at 30 N/mm² and strain controlled at a quasi-static nominal strain rate of 0.0025 1/s within the plastic region [10]. The tensile test specimen were machined from the initial sheets longitudinal to rolling direction (RD).

To evaluate the wear resistance of the tribology system two different test setups were considered. Based on [11] these two setups can be classified as simplified component test and component test. The component test was conducted using a setup described in detail by Kohlmann et al. [12]

### Table 1: Chemical composition of the different sheets tested as obtained by OES

|         | C  | Si | Mn  | P   | S   | Cr  | Mo  | Ni  | Nb  |
|---------|----|----|-----|-----|-----|-----|-----|-----|-----|
| HSLA    | 0.02| 0.03| 0.16| 0.015| 0.003| 0.05| 0.01| 0.04| 0.03|
| CS clad layer | 0.56| 0.30| 0.60| 0.018| 0.001| 1.46| 0.00| 0.04| >0.01|
| CS base layer | 0.06| 0.08| 1.34| 0.024| 0.002| 0.07| 0.02| 0.05| 0.09|
and run on a biaxial servo-hydraulic test bench (Powerflow Biaxial, SincoTec). Using this facility, the displacement is applied via the cross-beam and the torque is generated by a test bench shaft mounted underneath. Three steel discs made of low-carbon steel DC01 (C590) with a thickness of 2.15 mm were mounted to the cross beam with friction discs as spacer. The disc carrier was mounted to the shaft. The specimen ran in an oil bath being heated to 90 °C. A dynamic torque was applied to generate the surface pressure between the disc and the disc carrier, while the stroke of the cross-beam simulated the closing of the clutch. The torque curve was sinusoidal and synchronal with the stroke. The torque was increased with rising stroke until the turning point, to model the characteristic stress curve of a closing clutch. The test frequency was 8 Hz employing a stroke amplitude of 0.75 mm. The nominal surface pressure of 25 N/mm² employed was calculated based on Eq. 1 introduced for a straight tooth splined shaft connection in [13].

\[
p_m \approx \frac{2 \cdot T}{d_m \cdot L \cdot h' \cdot 0.75 \cdot n}
\]  

(1)

According to Eq. 1 the surface pressure depends on the torque \( T \), the reference diameter \( d_m \), the working depth \( h' \), the tooth length \( L \) and the number of tooth \( n \). The factor 0.75 considers the fact that due to pitch errors not every tooth suffers the same surface pressure. Since the surface pressure is a major parameter determining the wear behavior, the wear rate for the splined shaft connections is different for each tooth. This inherent system property is fully captured by the component test and, thus, the wear behavior of a real clutch is experimentally determined as close as possible based on a lab test. To compare the wear rate of different materials this, however, clearly is a disadvantage. The wear rate of single wear tracks cannot be compared since the actual surface pressure cannot be fully controlled. Thus, a simplified component test was designed. The wear behavior found based on this simplified testing setup was compared to that being observed in the component test to evaluate transferability of results. Afterwards, the simplified component test was used to compare the wear behavior of the CS with the HSLA reference condition. For the simplified component test, a pin-plate setup was used, where the CS and the HSLA reference alloy, respectively, served as plate material. Plates of 15 × 15 mm² size were cut out of the sheets and cleaned before testing. As pin not a simplified geometry was used, but a tooth that was cut by electrical discharge machining (EDM) from an actual disc with a thickness of 2.15 mm. Kohlmann et al. have shown that the manufacturing process of the discs has a strong influence on the wear properties of the tribological system [12]. Using the tooth of the clutch disc as pin, this important feature was taken into account and, thus, the actual wear behavior is thought to be much better represented than in case of using a simplified pin geometry.

The tooth was aligned with its tooth surface parallel to the plate as shown in Fig. 1b. The test bench used was a SRV3 Tribometer from Optimol. A load of 150 N was applied, resulting in a nominal surface pressure of 22.5 N/mm². The pin movement was linear with an oscillation frequency of 10 Hz and an amplitude of 1 mm. The test duration was 8 h, resulting in 288,000 loading cycles.
Fuchs Titan EG52529 was used as lubricant. All tests were carried out at ambient temperature.

For the wear characterization the topography of the wear marks were measured using confocal laser scanning microscopy (CLSM). The pin-plate test samples were measured using an Alicona InfiniteFocus. To analyze the worn tooth surfaces of the test disc carriers, the tooth were cut out of the disc carrier and characterized using a NanoFocus µSurf. Topography data were analyzed using the software µsoft analysis. The wear rates of the pins in the pin-plate tests were determined by measuring the mass loss.

To evaluate the manufacturability of the components considered, standard formability test for sheet metal like forming limit curves (FLCs) are not suitable. Forming of disc carriers can be categorized as bulk sheet metal forming featuring large accumulated strains and nonlinear strain paths. For these forming processes FLCs do not guarantee for valid results [14–16]. Thus, a bending test as shown in Fig. 2 was used for characterization of formability. The specimens of 2×20×50 mm² were bend up to 160° and then folded to 180° between two parallel plates. The bending surface was examined for cracks using optical microscopy as detailed above. A detailed discussion on suitability of the testing setup employed is beyond the scope of this paper and, thus, will be provided elsewhere [17].

3 Microstructure

Optical microscopy of the CS reveals that the speoridized 100Cr6 clad layer features a constant thickness of 90–95 µm. The base material consists of 85% ferrite and 15% perlite. Between the clad and the base material a 15–20 µm ferritic transition zone is visible. The HSLA reference condition shows a fine grained ferritic matrix with single perlite grains embedded (Fig. 3).

The different microstructures seen for the HSLA and the basematerial of the CS can be rationalized by the differing chemical composition and processing route. While the microstructure of the HSLA is established by an optimized
thermo-mechanical hot rolling process, the microstructure of the CS is mainly defined by the final heat treatment conducted, i.e. the spheroidize annealing (to be conducted for establishing an adequate 100Cr6 microstructure). The carbon content of 0.56 in the CS clad and the increased carbon content in the base material both indicate carbon diffusion from the clad into the base material.

4 Tensile tests

The stress-strain curves of the CS and the HSLA reference condition are very similar as shown in Fig. 4. The CS shows a slightly lower yield stress, however, the tensile strength and the uniform elongation for both materials are on an identical level, i.e. about 515 MPa and 14%, respectively. Lueders type behavior is more pronounced in the CS. As had been expected, the tensile properties of the CS are mainly determined by the base material due to its respective high volume fraction of 0.95. Thus, despite some minor differences as compared to the HSLA reference, the desired mechanical properties for the CS are obtained.

5 Wear test

As depicted in Fig. 5a, the surface after the component test shows a characteristic wear mark characterized by a maximum depth of about 60µm being shaped by adhesion and abrasion. The volumetric wear loss is calculated to 0.20 mm³. The profile in sliding direction has the shape shown in Fig. 5d. The characteristic features of the profile in the component test are primarily caused by the loading history. The characteristic features of the profile in the component test are primarily caused by the loading history. The applied dynamic torque is increased linearly with increased tooth displacement resulting in a maximum surface pressure on the left side and a minimum surface pressure at the right side of the wear mark. Hence, the depth of the profile increases steadily from the right to the left side. Perpendicular to the sliding direction the profile shows constant wear. The wear mark of the pin disc test (Fig. 5b) has a maximum depth of about 60µm as well. The volumetric wear loss is (as in case of the component test) 0.20 mm³.

Although the profile parallel to sliding direction (Fig. 5e) shows more pronounced wear on the left side, the 3D plot shows that this is a local phenomenon and not representa-
tive for the whole worn surface. The wear profile perpendicular to the sliding direction (Fig. 5h) shows higher wear at the left side, probably caused by misalignment between pin and plate resulting in a slightly inhomogeneous surface pressure. Thus, even though the wear mark profiles of the test setups reveal some minor differences, the general wear behavior of the component test can be reproduced using the pin-plate test. Eventually it can be concluded that it is possible to compare the wear rates of the CS with the HSLA reference condition in the tribologic system disc carrier/disc using the pin-plate test.

For the contact pair HSLA/DC01 wear of the plate is high, while the wear of the pin is relatively low (Fig. 6a). The pin leads to severe wear of the plate surface as the former is characterized by a relatively high hardness. Pronounced hardening of the pin is imposed by fine blanking, where the cutting edge of the pin is work hardened. The difference in hardness between the work hardened cutting edge and the unaffected core of the pin is shown in Fig. 6b. Compared to the HSLA, wear of the CS plate is reduced by an order of magnitude, however, wear of the pin is strongly increased as shown in Fig. 6a. For the contact pair CS/DC01 the CS plate primarily wears the pin. Thus, clearly the wear resistance of the CS is higher than the wear resistance of the HSLA. The wear resistance is not increased by higher hardness of the clad but by the hard carbides being present in the ductile ferritic matrix of the 100Cr6 Clad inhibiting abrasive wear [18]. The combined wear is lower for the contact pair CS/DC01 as compared to the HSLA/DC01. As detailed above, for the CS/DC01 pairing the wear mainly occurs on the pin and not the plate. This is of high importance as wear at the tooth surface of the disc carrier will create grooves. These grooves eventually negatively affect the torque capacity of the friction clutches.

6 Bending test

After bending and folding, the HSLA reference condition shows evolution of pronounced surface topography, strain localization in form of shear bands and distortion at the outer surface. These observations are known for bending of aluminium alloys, where the elementary mechanisms of failure during bending are well studied [19–21]. It is assumed that the damage mechanisms for bending of the monolithic steel considered are somehow similar.
Towards the outer radius the large tensile strains cause ductile damage leading to the evolution of strongly elongated voids parallel to the bend surface. Beside these voids, no cracks or major ruptures are found in the material. While no cracks occur during bending of the CS to 160°, in the 180° folded specimen necking and rupture of the clad is observed. The absence of any signs of delamination reveals the high bond strength of the interface. Only some minor ductile damage is observed in the clad as well as in the base material (Fig. 7).

The volume affected by necking is smaller in the HSLA than it is in the CS. While in the CS necking only is seen in the 100Cr6 layer, in the HSLA several grains display severe distortion. For the HSLA effects seem to be on the grainsize level, however, for the CS the thickness of the necking area equals the clad layer thickness. Even though the CS shows cracks after folding to 180°, its formability is very high. At this point it has to be emphasized that the formability required in the forming process of the disc carrier is less than absolute forming limits tested in the bending test.

7 Conclusion

The present study aimed at evaluating the usability of a cladded steel to be employed for disc carriers. For this reason general mechanical properties, formability and wear resistance of a cladded steel made from a micro-alloyed low carbon steel base material and a thin 100Cr6 layer as compared to commonly used monolithic micro-alloyed low-carbon steel were evaluated.

A pin-plate setup was derived from an established component test for the tribological system disc carrier/disc to evaluate the wear resistance. The formability of the two materials was compared using bending test.

The wear resistance of the CS is found to be superior to the HSLA due to its specifically tailored microstructure. In the bending test the CS shows high formability, i.e. bending angles up to 160° without cracking of the thin clad surface layer. Cracks only occur upon folding to 180° for the CS, a value that is not reached during forming of the actual component envisaged. Thus, the results clearly reveal that a cladded steel can be used to improve the wear resistance in clutch applications while still having good formability eventually providing for an excellent alternative to high-cost current state-of-the-art materials.

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