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Laser micro structuring of multi-layer coatings on aircraft splines for optimization of the surface properties

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Abstract

In the aircraft industry spline-joints are used for the connection of subassemblies in geared turbofans. Besides the power transmission, spline-joints are used to compensate deviations in the shaft system, such as angular or axial misalignments. By decoupling the subassemblies, constraining forces are reduced, which affects the dimensioning of the surrounding components. Increasing the load capacity of spline-joints enables a lean and efficient design of the components. The wear behavior of such heavily loaded splines can be improved by multi-layered coatings deposited e. g. by physical vapor deposition (PVD). Further improvements can be realized by an additional laser structured surface topology, which includes an arrangement of semi-spheres in the coating system with diameters in the micrometer range. These semi-spheres can either serve as a micro pocket for lubrications or are applied before the final coating step to be replenished with a hard lubricant layer. This paper addresses this subject by presenting the manufacturing process of splines with focus on the laser texturing process.

Keywords: Laser micro structuring, PVD-coatings, Wear behavior

1 Introduction

To connect subassemblies and to transmit high torque, spline-joints are used in powertrain technology [1]. Spline-joints are furthermore used in modern aero-engine-turbines to connect shaft systems and compensate shaft misalignments [2]. This enables to raise potentials according to the required packaging volume and components weight of the whole system, which leads to an increasing power density. Overall, manufacturing costs can be cut because of a reduced need of material and the system efficiency is increased, while simultaneously the system emissions are decreased due to reduced inertia [3]. Due to the compensation of the misalignment of the shaft systems, a sliding velocity is generated in the spline-joint contact between the teeth of the spline-shaft and -hub. Therefore, the risk of upcoming wear and fatigue phenomena is raised on the tooth flanks [4]. To minimize wear effects and raise the load carrying capacity of spline-joints, new optimized surface treatments are developed, see Fig. 1.

In a first step, Stephen et. al. has developed possible surface treatments for the optimization of the load carrying capacity of spline-joints [5]. Different coatings have been selected for the upcoming full scale spline testing. Therefore, TiN + MoS_2:Ti and TiN + DLC + MoS:Ti:C multi-layered coatings are manufactured by physical vapor deposition (PVD). Additionally, a laser structuring process is applied, where dimple textures are manufactured on the tooth flanks [5]. As known, surface texturing is an effective way of improving tribological properties under both dry and lubricated conditions [6]. Its main effect mechanisms are to trap wear particles, store lubricants, and increase load carrying capacity [7].

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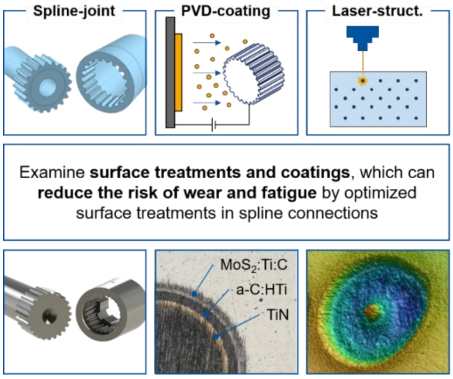

Fig. 1: Manufacturing steps for high-loaded splines for aerospace applications in fan-turbines

Nevertheless, the influence of texturing parameters, like dimple diameter and density, spatial arrangement and aspect ratio on friction forces is not explicitly known at all, as it depends on many different conditions of the tribological system. Variations of the dimple diameter showed that there is an optimum in the dimple diameter and that this optimum depends on the oil viscosity and the velocity gradient along the contact area [8]. The aspect ratio [9] and the textured area [10] widely influence the tribological properties of the texturing. Besides structuring, hard coatings are used to increase the wear resistance, e.g., multi-layer PVD coatings. Especially, in case of aircraft applications for turbine engines, high contact pressures of more than 1 GPa and a partially lubrication lost due to air holes while flying occur. Therefore, in defined multi-layer systems with respect to the diameter of the structured dimples and their density also should be of most importance to improve the tribological properties according to decreasing friction and wear.

2 Method

An ultrashort pulse laser with a wavelength of 1030 nm was used as the laser beam source for structuring the multi-layer systems. The laser used (Trumpf TruMicro 5050) has a pulse length of less than 10 ps with a maximum output power of 50 W and a pulse repetition rate of 200 kHz. The laser beam was guided over the workpiece by a Galvano scanner with a focus diameter of 40 µm. The spline was clamped into a rotational stage mounted on xyz-stages for positioning, see Fig. 2. The laser texturing by the scanner after positioning was performed without a protective gas supply. Applied to the multi-layer systems were four different textures varying the dimple diameter and the dimple density. The dimple diameter is indicated as d with a pitch a hexagonally orientated leading to a dimple density of A, i.e., the percentage of surface area covered by dimples, see Fig. 3.

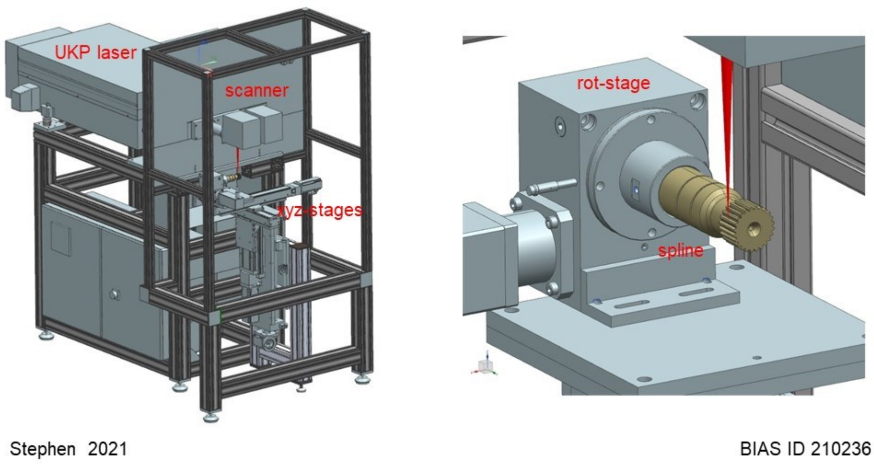

Fig. 2: Machining system (left) and detailed view of the spline machining arrangement (right)

Based on the chosen coating designs and laser structuring parameters, a full factorial design of experiments (DoE) was applied to systematically analyze the effect of the input factors [5]. These factors are the dimple diameter, the remaining coating coverage, the coating system, and the process design. On the last point, structuring of all coating layers is compared to structuring of only the hard coating layer (TiN/a-C:H:Ti) and subsequent application of the solid lubricant. One example from the full factorial design applied to splines will be discussed in the following.

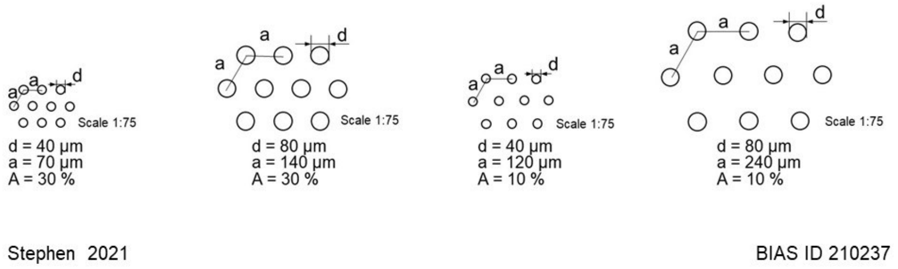

Fig. 3: Different textures defined for the laser structuring

3 Results and discussion

A corresponding laser confocal microscope image and an EDX analysis of a multi-layer system consisting of TiN + MoS_2:Ti applying a dimple diameter of 40 µm and a dimple density of 10 % are shown in Fig. 4. The 3-dimensional measurements indicate a constant depth of 1 µm for all measured micro dimples, see Fig. 4 (left). This results by choosing a suitable laser pulse energy (5 µJ) and pulse repetition rate (50 kHz), that the ablation could be set in such a way that the MoS_2:Ti layer on top was removed which have a depth of 1 µm. Furthermore, the underlying layers retained on the substrate as proved by EDX analysis also shown in Fig. 4 (right). This is indicated by the fact that the Mo and S signals decrease nearly completely whereas that of Ti increases inside of the dimple. The number of applied scans for processing was 5 at a constant speed of 250 mm/s. The depth can be reproducibly set with an absolute deviation of less than 0.2 µm. The evenness of the dimples is in the range of ± 0.1 µm. Almost no burr formation or melt residues are observed.

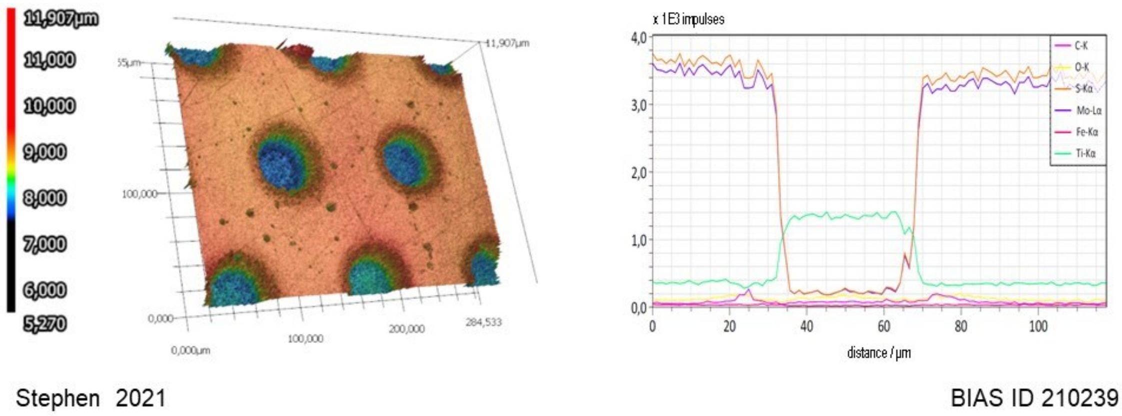

Fig. 4: Laser Confocal Microscopy and EDX analysis of an laser structured multi-layer system (TiN + MoS_2:Ti; d = 40 µm, A = 10%)

The process development and analysis were performed on flat discs with structure dimensions of 20 mm times 20 mm for enabling pin-on-disc test to evaluate the surface properties regarding friction and wear behavior. A challenge for laser texturing of the splines is the more complex geometry, i. e. curved surface on the partially shadowed flank, see Fig. 5. Therefore, a precise adjustment of the laser beam in lateral and axial position must be realized to ensure an almost perpendicular incidence of the laser beam deeply on the flank side as shown in Fig. 5 (right). The individual 24 left- and right-handed flanks are textured using a fixed laser beam position and precisely rotating, respectively laterally moving the spline into the correct position after finalizing each flank itself. Indeed, the focal position must be identical for each flank and concentrically located in the flank taking the Rayleigh length of the laser beam into account.

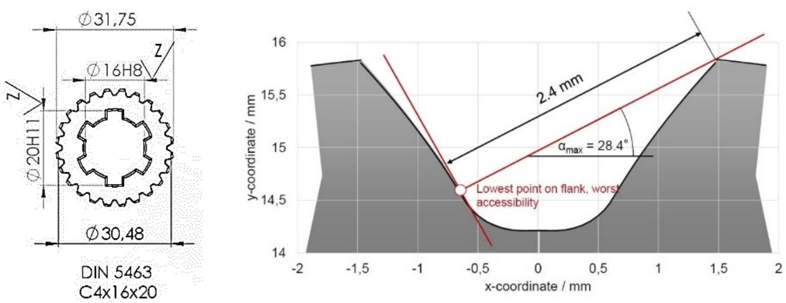

Fig. 5: Geometry of the splines in cross-sectional view (left) and necessary incidence of the laser beam (right)

Applying such a texturing strategy using the developed processing technology the complete spline flanks can be evenly machined. Depending on the size and density of dimples the splines are covered with 25,000 to more than 100,000 dimple structures in less than 1 hour machining time. Indeed, the bottom of a flank will not be textured, and the top is slightly influenced by the touching laser beam, see Fig. 6. However, these areas are not affected by high loads and therefore not critical for the friction and wear behavior.

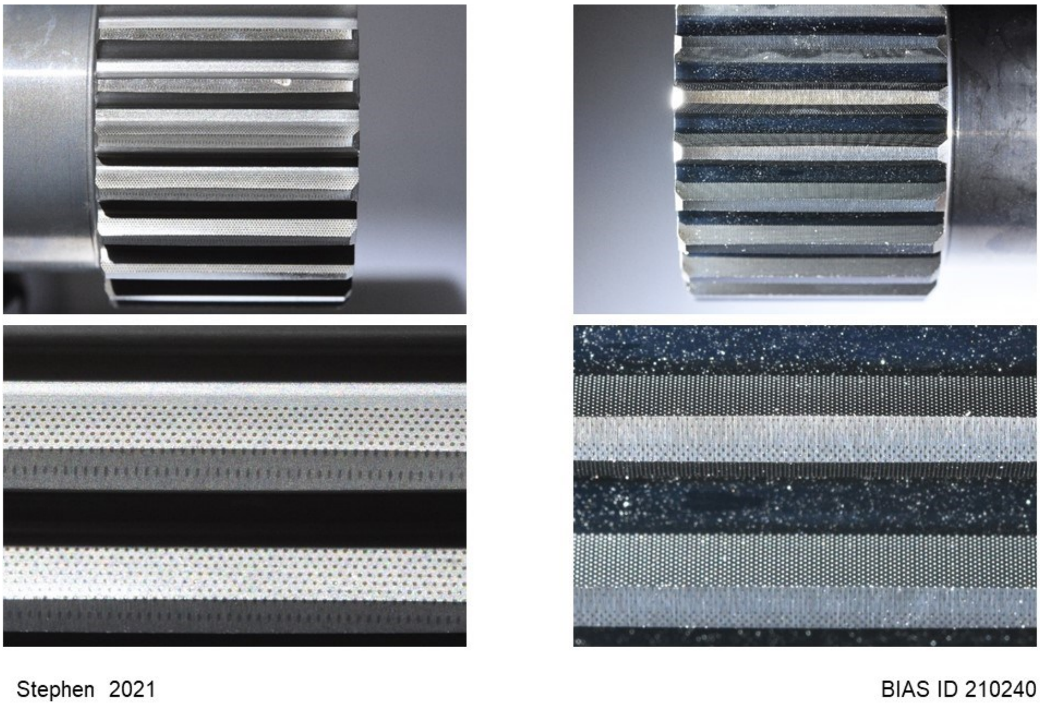

Fig. 6: Textured splines overall view and in magnified detail: left: d = 80 µm, A = 10%, right d = 40 µm, A = 10%

4 Conclusion

The manufacturing process focused on a laser texturing step for surface optimized spline-joints has been presented. The spline has been manufactured within a conventional process chain, which is likely to be used in aero-gear-applications. The innovation is the combination of laser and PVD processes suitable to perform on splines obtaining a surface modification which can be applied for highest contact pressure applications.

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References

[1] C.H. Wink, M. Nakandakar: Influence of Gear Loads on Spline Couplings. Power transmission Engineering (2014) 42–49.
[2] J. Ding, I.R. McColl, S.B. Leen: The application of fretting wear modelling to a spline coupling. Wear 262/9-10 (2007) 1205–1216.
[3] H.E. Friedrich, S.K. Krishnamoorthy: Leichtbau als Treiber von Innovationen. Leichtbau in der Fahrzeugtechnik. Springer (2017) 1–31.
[4] F. Curà, A. Mura, S. Ugarte, P. Saenz: Recent Advances in Spline Couplings Reliability.Proc. Structural Integrity 19 (2019) 328–335.
[5] A. Stephen, B. Lenz, A. Mehner, T. Radel: Laser structuring of PVD multi-layer systems for wear reduction. Lasers in Manufacturing (2021).
[6] Z. Wu, J.X. Deng, Y. Chen, Y.Q. Xing, J. Zhao: Performance of the self-lubricating textured tools in dry cutting of Ti-6Al-4V. Int. J. Adv. Manu. Technol. 62 (2012) 943–951.
[7] Y.Q. Xing, J.X. Deng, Z. Wu, H.W. Cheng: Effect of regular surface textures generated by laser on tribological behavior of Si3N4/TiC ceramic. Appl. Surf. Sci. 265 (2013) 823–832.
[8] C. Greiner, T. Merz, D. Braun, A. Codrignani, F. Magagnato: Optimum dimple diameter for friction reduction with laser surface texturing: The effect of velocity gradient. Surf. Topogr. Metrol. Prop. 3 (2015) 044001.
[9] A. Shinkarenko, Y. Kligerman, I. Etsion: The effect of elastomer surface texturing in soft elasto-hydrodynamic lubrication. Tribol. Lett. 36 (2009) 95–103.
[10] X.L. Wang, K. Kato, K. Adachi, K. Aizawa: The effect of laser texturing of sic surface on the critical load for transition of water lubrication mode from hydrodynamic to mixed. Tribol. Int. 34 (2001) 703–711.