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Tailored Forming of Hybrid Bevel Gears with Integrated Heat Treatment

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Abstract

"In recent years, multi-material designs of technical components have been gaining in importance. When combining different materials in a single component, it is possible to achieve high performance and extended functionality while simultaneously saving cost-intensive or rare materials. One promising approach to manufacture hybrid parts such as bi-metal gears is the utilization of the technology of tailored forming. This technology includes three main process steps: producing of bi-metal workpieces, forming and finishing. At the example of bevel gears, bi-metal preforms were produced by laser cladding of the martensitic steel X45CrSi9-3 on a cylindrical substrate made of the carbon steel C22.8 and formed to the final gear geometry by means of hot die forging. Subsequently, the hot bevel gears were directly quenched from hot-forming temperature by an air-water spray and self-tempered using the residual heat. To analyse the effect of each process step on the microstructure, specimens were extracted from cladded, forged and heat treated components and investigated by means of metallographic analysis and hardness measurements. The results demonstrate that cladded workpieces were successfully formed to complex toothed parts without any defects. The hot forming process has a positive impact on the welded layer and the interface zone by grain refinement and the associated improved mechanical properties. The required hardness values at the tooth flanks were achieved by the integrated heat treatment."

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Keywords: Tailored forming; Hot die-forging; Bevel gear; Bi-metals; Process-integrated heat treatment, Air-water spray cooling

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1. Introduction

Conventional parts made of a single material cannot meet continuously growing demands regarding improved efficiency while maintaining low costs due to their material-specific limitations. In contrast, multi-material component designs combining various benefits of individual materials represent a promising approach to manufacturing bulk components with advanced functionality and application-optimized properties [1]. Multi-material concepts can be applied to all components requiring diverse properties in different areas of the part. In this context, the development of new production technologies for manufacturing multi-material components has become a focus of many research projects.

For example, Plancak et al. implemented analytical and experimental tests on the upsetting of coaxial bimetallic workpieces consisting of two different steels (C15E/C45E) [2]. Wohletz and Groche investigated the joining of steel and aluminium raw parts (C15/EN AW-6082 T6) by means of a combined forward and cup extrusion [3]. Behrens et al. studied the compound forming of bi-material shafts by indirect impact extrusion of different steel combinations such as a structural steel S355J and a heat-treatable steel 42MoCr4 [4]. In particular, the manufacturing of bi-metal gears has been implemented using technologies such as shrink fitting, friction welding [5] or bi-metal casting [6]. However, only a few results exist regarding bulk metal forming of bi-metal gear wheels. The key concept applied in these investigations was compound forging, where the joining of different materials and the

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forming to the final geometry are combined in a single stage. Politis et al. examined the effect of tooling and interfacial friction on the material flow behaviour during forming of bi-metal gears by numerical simulation and experiments [7, 8]. For this approach, different tooth ring thicknesses and different material combinations, such as steel-aluminium, steel-lead, steel-copper and copper-lead, were used. Wu et al. carried out similar research for a steel-aluminium-combination focusing on the gap size and height difference between ring and core [9]. The investigations mentioned above primarily consider the material distribution in the interfacial zone but not the microstructure-based bonding quality after forming. The key challenge of joining by forming is to produce the metallurgical bonding between raw parts.

The central challenge in joining by forming is the creation of the metallurgical bond between the raw parts. For achieving this, specific process conditions such as temperature, contact pressures and relative movement between the materials are required. This results in a narrow process window, which is difficult to ensure when forming complex components due to process-related varying strains and non-uniform material flow. Furthermore, the joining quality improves with increasing forming temperature, but there is a risk of scaling, which can have a negative influence on the composite properties. For this reason, the use of already joined semi-finished products with an existing metallurgical bond is advantageous in the compound forging of complex components in order to obtain uniform properties in the composite zone. This method has been investigated in several works.

Klotz at al. performed the isothermal forging of bi-metal gas turbine discs made of two different Ni-based superalloys from hot isostatically pressed billets [10]. Behrens et al. implemented the co-extrusion of non-centric steel-reinforced aluminium profiles with subsequent forging [11]. Domblesky et al. carried out hot compression tests in order to study the forgeability of friction-welded bi-metal pre-forms combining copper, aluminium and steel [12]. Frischkorn et al. investigated the hot forging behaviour of further material combinations comprising steel, aluminium, titanium and Inconel [13]. Wang et al. conducted numerical and experimental investigations on the hot upsetting of bi-metal billets produced by weld cladding (C15/316L) [14].

The current research demonstrates the potential for creating hybrid bevel gears by the technology of tailored forming, which is characterised by bulk forming of previously joined materials. The main objective of this approach is to improve the microstructure and the mechanical properties of welded preform by thermo-mechanical processing during the forming operation. In the case of bevel gears, the process chain starts with cylindrical cladded preforms, which are subsequently formed to the toothed geometry. The forged bevel gears are directly heat-treated by quenching from hot-forming temperatures to increase the strength and hardness of the tooth flanks. In the following, the developed tooling and the main steps of the experimental setup are described as well as the possibility to improve the microstructure and hardness in the joining zone.

2. Manufacturing of hybrid bevel gears

2.1. Initial and final geometry

Depending on the operating conditions, some regions of the bevel gear are exposed to higher mechanical stresses than others. Due to tribological contact under cyclic loads, the tooth flanks undergo higher stresses compared to the rest of the part. For this reason, high performance materials (such as high-strength steels) resistant to rolling stresses are required at the tooth flanks. However, the usage of a high performance material for the whole component would be expensive. With the proposed multi-material approach, it is possible to replace cost-intensive materials in regions of the structural part that are located outside the critically stressed areas. Thus, resource-savings can be achieved and cost-efficient parts can be produced.

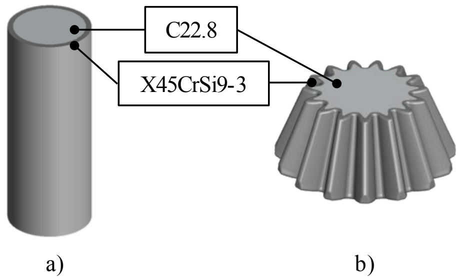


Fig. 1. Cladded workpiece and demonstrator part.

The investigated straight bevel gears consist of a martensitic valve steel X45CrSi9-3 on the toothed surface and a carbon steel C22.8 in the core. The corresponding semi-finished workpieces were designed in accordance with the load collective of the final parts. The demonstrator part and the workpiece are illustrated in Fig. 1. Their most important geometric parameters are presented in the Table 1. The hybrid workpieces are produced by laser hot-wire cladding, turned to a diameter of 30 mm and subsequently formed to the final geometry by hot forging.

Table 1. Geometry of the initial workpieces and the parameters of the straight bevel gears.

Cladded workpiece	
Outer diameter	Ø 30 mm
Core diameter	Ø 27 mm
Height	78 mm
Hybrid bevel gear	
Number of teeth	15
Module	3.5
Transmission ratio	1:3
Outer diameter	Ø 62 mm
Height	30 mm

2.2. Die forging

The die forging of the bi-metal bevel gears was performed in a fully automated forging cell depicted in Fig. 2. It consists of a screw press (Lasco SPR500), an induction heating unit and a programmable handling robot with an adjusted gripper device.

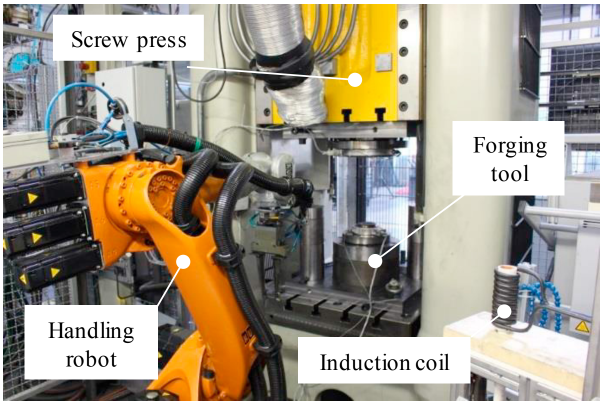


Fig. 2. Automated forging cell.

For the experimental forging tests, a single-stage forming tool system designed modularly in accordance with the final bevel gear geometry was integrated into the forging press (Fig. 3). The forming of the outer geometry is carried out by a lower die and a pre-stressed geared die, which is installed in the upper tool in order to ensure a smooth removal of the forged gears. Both forging dies are heated to a temperature of approx. 200 °C with heating sleeves. The maximal capacity of the screw press is 40 kJ. An automated process control ensures a high reproducibility of the forged parts.

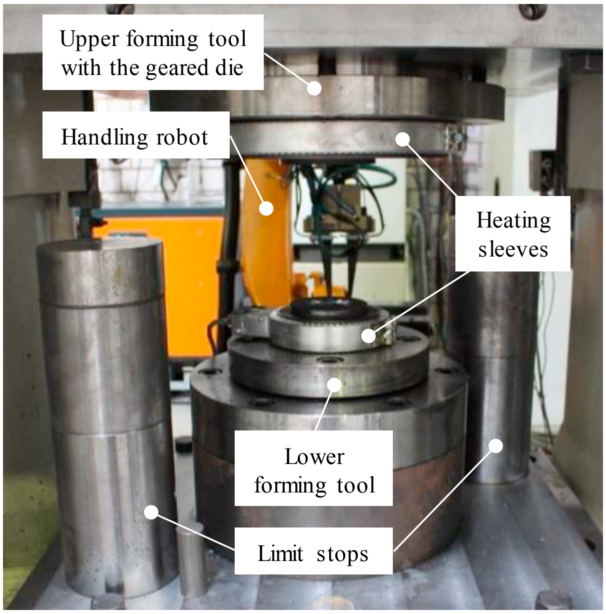


Fig. 3. Forming tool system for die forging of bi-metal bevel gears.

For preliminary tests, the workpieces were heated in a chamber furnace up to a temperature of 1100 °C and subsequently forged. However, this concept did not allow the mould to be filled completely as depicted in Fig. 4a. This can be explained by a high deformation resistance in the toothed area, which had a negative impact on the material flow in the narrow part of the bevel gear. Therefore, an increased volume of forging flash formed.

Fig. 4 Comparison of form filling between hybrid bevel gears forged with a uniform (a) and non-uniform (b) temperature profiles.

In order to improve the mould filling, a modified heating concept with an inhomogeneous temperature distribution along the workpiece length was developed. For this approach, an induction unit connected to a middle frequency generator (Huettinger TruHeat 3040) with a maximum power output of 40 kW was used. The required temperature gradient was achieved by axially positioning the workpiece off-center in the induction coil and by using the electromagnetic end effect, which appears at the edge area of workpiece during the heating [15]. Subsequently to the induction heating with a duration of 28 s, the hot workpieces were ejected from the induction coil and automatically transported to the forging press within 6 s. The resulting temperature distribution prior to the forging is shown in the thermographic image depicted in Fig. 5a.

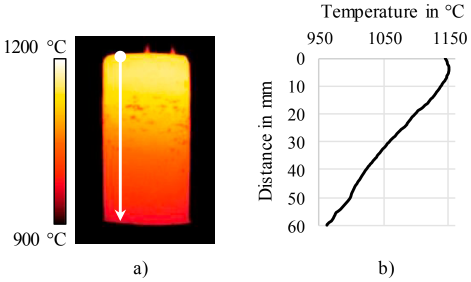


Fig. 5. Thermographic image of the cladded workpiece (a) and temperature profile prior to forging (b).

As shown in Fig. 5b, the temperature prior to forging varies between 950 °C and 1150 °C along the length of the workpiece. Using this improved strategy featuring an inhomogeneous temperature profile, a complete mould filling without any outward forging defects (e. g. folds) was achieved in a single forging step, even in the crucial toothed area in the upper part of the bevel gear (Fig. 4b). The most important forging parameters employed are summarised in Table 2. For the subsequent processing step, the hot forged bevel gears were transported to the air-water spray cooling device for a process-integrated heat treatment by quenching from hot-forming temperature.

Table 2. Forging process parameter.

	Parameters
Forming temperature profile	950-1150 °C
Tool temperature	200 °C
Provided energy	20 %
Forging force	Approx. 510 kN
Height reduction	62 %

2.3. Process-integrated heat treatment

Following the forging process, the hot forming temperature is exploited for a process-integrated surface hardening by quenching utilizing an air-water spray cooling. The surface hardening is realised by a short intensive cooling for the generation of a martensitic surface layer and a subsequent self-tempering of this surface layer by the flow of residual heat from the core of the component [16]. The spray cooling system developed for the process-integrated heat treatment of the bevel gears is depicted in Fig. 6.

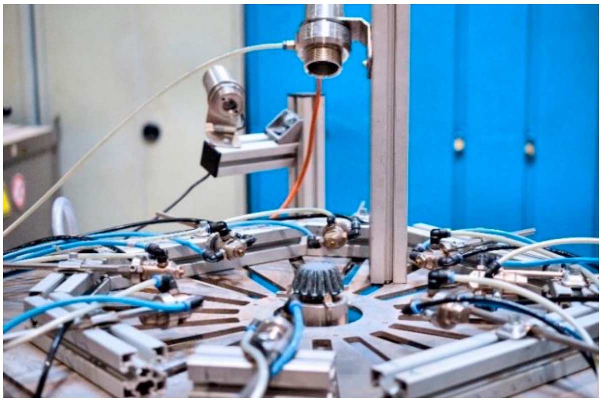


Fig. 6. Spray cooling system for bevel gears.

The spray cooling system consists of a rotating mount for the bevel gear and eight annularly arranged air-water spray nozzles aligned with the axial centre of the bevel gears at a distance of 100 mm from the workpiece surface. The cooling rate can be adjusted by different air and water inlet pressures. A short first quenching phase with a high cooling effect produces a martensitic surface layer in the toothing area of the workpiece. Subsequently, the residual heat remaining in the bevel gear can be used to temper this surface layer while a predominantly bainitic core structure is formed simultaneously. To control the self-tempering temperature, a pyrometer was used to monitor the surface temperature in the tooth tip during the self-tempering phase. When employing a cooling by compressed air during tempering, this measurement can be carried out continuously; otherwise, the measurement is only possible between two air-water spray pulses. A second pyrometer measures the temperature on the front side and ensures a uniform starting temperature for heat treatment after transportation of the forged bevel gears from the forging press to the spray cooling system.

Table 3 shows the parameters employed for the heat treatment of the bevel gears. The spray parameters and the duration of the quenching phase were determined by means of numerical simulations of the process-integrated surface hardening and tempering. The heat treatment coefficients were estimated by cooling tests on bevel gears. Boundary conditions were correspondingly adapted in the calculation of the cooling curves by a numerical simulation of the quenching process as described in [17].

Table 3. Heat treatment parameters of hybrid bevel gears

	Parameters
Start temperature	1000 °C
Duration 1st phase	8 s
Cooling medium 1st phase	Air-water Spray
Tempering temperature 2nd phase	600 °C
Duration 2nd phase	73 s
Cooling medium 2nd phase	Air-water Spray

2.4. Metallographic preparation

For a metallographic examination and micro hardness measurements, samples were cut from the bevel gears at two positions (Fig. 7). The lower part of the bevel gear (Position A) undergoes a higher plastic strain during forming (1.2–1.4 in the tooth tip and up to 3.0 in the tooth root) than the upper part (Position B, 0.8–1.0 in the tooth tip and up to 2.2 in the tooth root) [18]. Due to the different removal heights, it is possible to analyze changes occurring in the joining zone for the varying plastic strain and temperature.

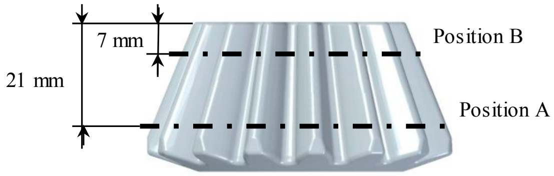


Fig. 7. Sampling positions for metallographic examination and hardness measurements.

After metallographic preparation microsections of the tooth tip and root were taken. A microhardness measurement was carried out in the tooth tip and root areas according to Vickers (HV 0.5) in the radial direction from the edge to the centre of the specimen (Fig. 8).

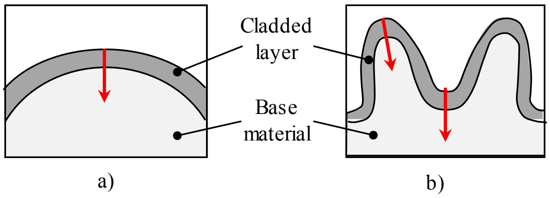


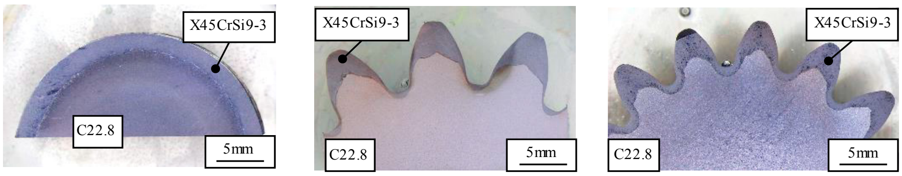
Fig. 8. Positions of the micro hardness measurements in the workpiece (a) and in the bevel gear (b).

3. Results and discussion

In the following, the results of the metallographic investigations and the hardness measurements are presented for the cladded workpieces, for forged bevel gears after uncontrolled air cooling and for forged bevel gears after an integrated heat treatment. The macrographs in Fig. 9 show the material distribution after cladding (Fig. 9a) and after forging (Fig. 9b und c). The interface zones are free of defects like cracks, separations or porosity and feature a complete metallurgical bonding of the substrate with the cladding material after welding and after forming. The non-uniform distribution of the clad material after forming can be explained by different local strain rates in the tooth tip and root. In the tooth root zone, the material experiences higher radial deformation, which leads to a higher reduction of the clad layer thickness. In contrast, the cladded layer in the tooth tip zone shows a small increase in maximum thickness due to axial upsetting during forming. Fig. 10a shows the initial microstructure of the joining zone resulting from laser wire deposition welding of X45CrSi9-3 onto the base material C22.8.

The core microstructure contains a mixture of ferrite and pearlite typical for low carbon steels. Close to the joining area, a heat-affected zone with plates of Widmanstätten ferrite can be observed that forms due to heat exposure and structural transformation during the welding process. According to the hardness profile in Fig. 10c, the basic hardness in the core is about 154 HV 0.5. In the joining zone, a thin layer (10 µm) consisting of pearlite can be seen. Fig. 10b illustrates the solidification structure of the clad material with a formation of fine pearlite at the primary austenite grain boundaries as well as pearlite nodules. The average hardness of the coating is more than twice as high as that of the base material and amounts to 379 HV 0.5.

Fig. 11a and b illustrate the microstructure of forged bevel gears cooled in still air at position A. Similar to the workpiece, the base material has a ferritic-pearlitic microstructure in the tooth root as well as in the tooth tip. The Widmanstätten structure close to the joining zone is not present after forming anymore, while the pearlitic interlayer between the two steels is retained. The interlayer thickness is up to 50 µm in the tooth tip and up to 20 µm in the tooth root. The microstructure of the clad layer consists of a mixture of martensite and pearlite. In comparison to Fig. 10b, the initial weld microstructure is smoothed and more regular. The grain refinement is resulting from recrystallization processes due to plastic strains during the hot forming. The microstructural differences correspond with the micro hardness values (marked with red in Fig. 11e and f). Compared to the initial microstructure of the workpieces, a larger pearlite fraction in the coating has arisen after the cooling of the forged bevel gear. Hence, the clad material has a lower average hardness of 279 HV 0.5 in comparison to the hardness after welding (cf. Fig. 10c). The micrographs of the forged bevel gear at position B (Fig. 13a and b) show a pearlitic-martensitic microstructure similar to the microstructure at position A. However, differences between the grain sizes of primary austenite in the clad material can be clearly seen, especially in the tooth tip.



a) b) c)

Fig. 9. Macrostructure of the interface zone in the cladded workpiece (a) and in forged bevel gears at position A (b) and position B (c) in transversal cross section.

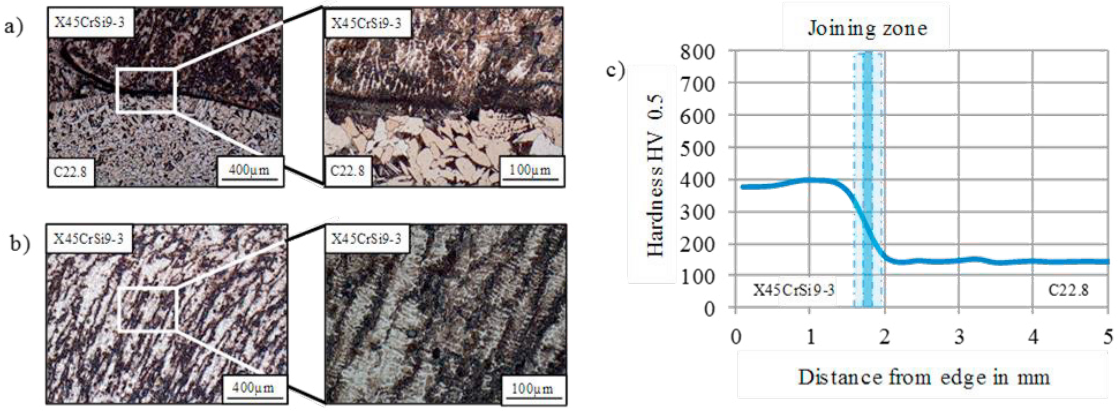


Fig. 10. Exemplary micrographs (etched with Beraha II) of the interface zone (a) and the clad material (b); micro hardness profile HV 0.5 (c) in a bi-metal workpiece.

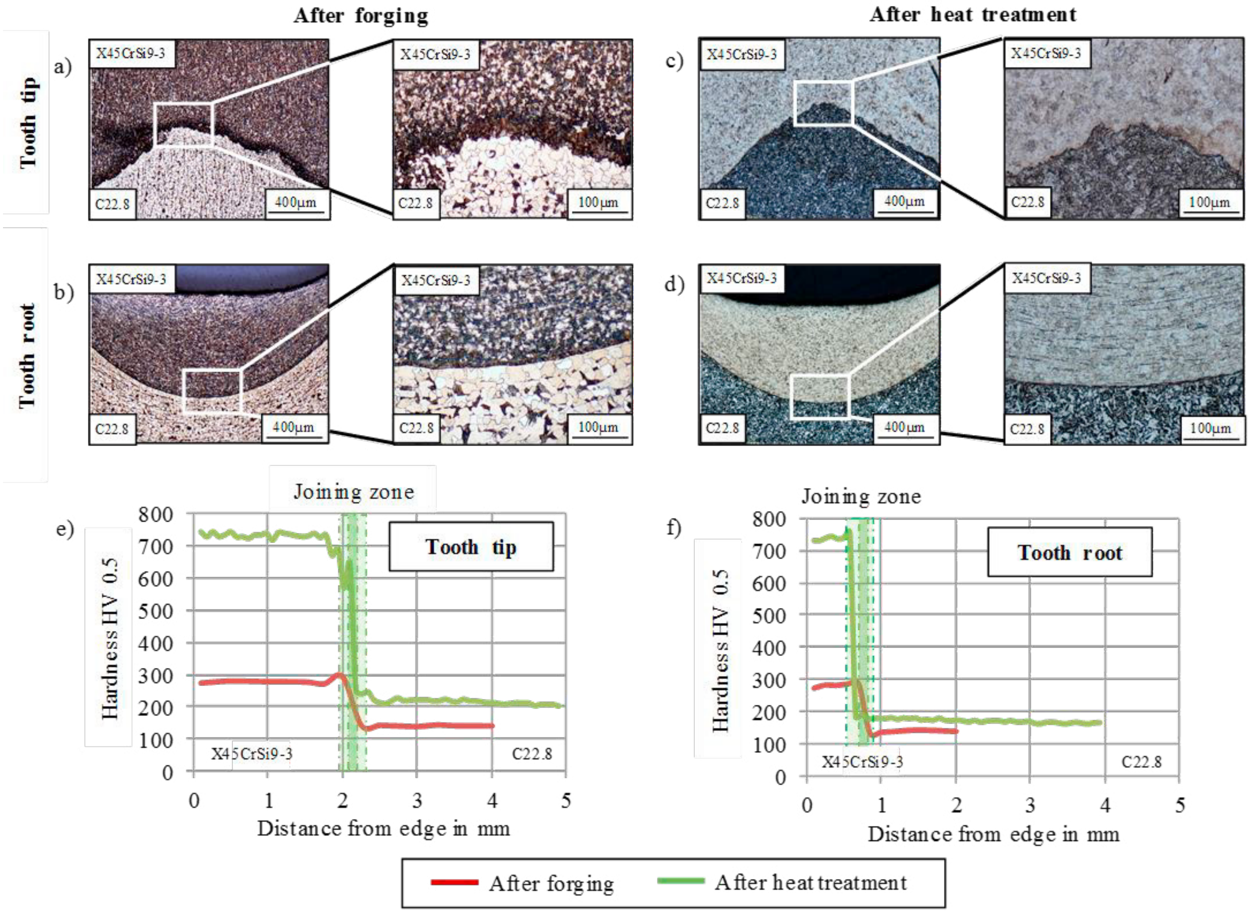


Fig. 11. Exemplary micrographs of the interface zone in forged bevel gears at position A: after forming in the tooth tip (a) and in the tooth root (b) etched with Beraha II, after heat-treatment in the tooth tip (c) and in the tooth root (d) etched with V2A etchant; and micro hardness profiles HV 0.5 in the tooth tip (e) and in the tooth root (f).

This can be explained by lower plastic strain and higher forming temperature in the upper part of bevel gear, where the recrystallization took place just on some of the grains and the coarse primary austenitic grains remain after deformation. Austenite grain growth during heating can be neglected due to the short heating time during induction heating. Fig. 12 illustrates the needle-like martensitic microstructure within prior austenite grains at higher magnification. As shown in Fig. 13e and f, the hardness values after forming in the layer at position B are higher compared to position A (Fig. 11e and f). The local variations of hardness values (position B) in the layer (e. g. between 400 and 600 HV 0.5) are caused by the individual microstructural phases in which the hardness indentations are placed. The base hardness of the substrate material C22.8 has not changed after forming and amounts to 150 HV 0.5 in the upper as well as in the lower part of the bevel gear.

Fig. 11c, d, f and Fig. 13c, d, f show micrographs and micro hardness curves of the bevel gears after forging and process integrated heat treatment. In comparison to the bevel gear cooled at still air, the cladded material after heat treatment shows tempered martensite in bevel gear positions A and B, especially in the tooth tip. The microstructure of the tooth root also contains martensitic microstructures. This is confirmed by the performed micro hardness measurements, which show hardness values of 600 to 750 HV 0.5 near the surface.

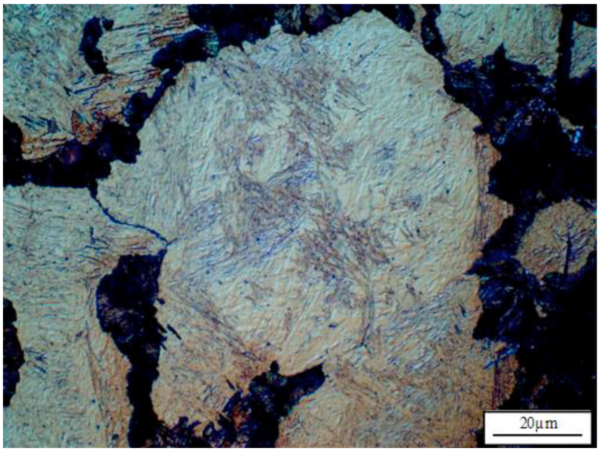


Fig. 12. Differential interference contrast micrograph of martensitic structure in the clad layer in the tooth tip at Position A (etched with Beraha II).

The higher cooling rates during process-integrated heat treatment prevented the formation of a pearlite structure and produced a hardened martensitic surface layer. Furthermore, the heat treatment influenced the intermediate layer between the two steels, especially in the tooth tip. It is either partly suppressed in the tooth tip (high strain position A) or entirely suppressed in the tooth tip (low strain position B). There is a transition between the martensitic tempering structure of the cladded steel and the martensitic tempering structure of the carbon steel in the vicinity of the original joining zone, in which the ferritic-pearlitic components predominate towards the core, as can be seen from the micro hardness curves. The area of the tooth root features a different structure of tempered martensite in the coating material and a ferritic-pearlitic structure in the base material with a pronounced intermediate layer. A possible reason for this is the lower cooling rate close to the tooth roots which leads to a lower martensite fraction especially in the base material.

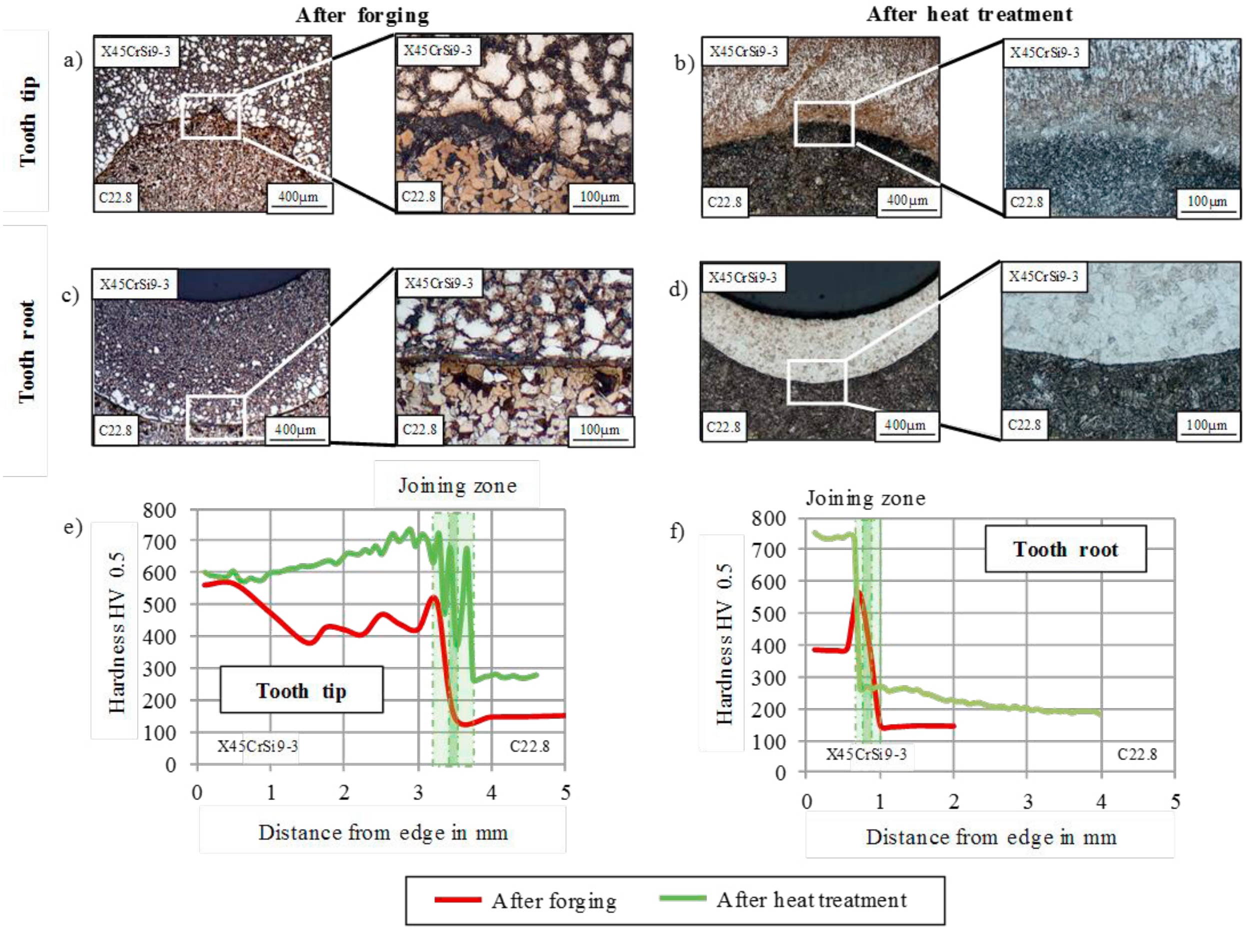


Fig. 13. Exemplary micrographs of the interface zone in forged bevel gears at position B: after forming in the tooth tip (a) and in the tooth root (b) etched with Beraha II, after heat-treatment in the tooth tip (c) and in the tooth root (d) etched with V2A etchant; and micro hardness profiles HV 0.5 in the tooth tip (e) and in the tooth root (f).

4. Conclusions

The coarse, inhomogeneous weld structure produced by laser cladding can be homogenized and refined by means of hot forming. The resulting microstructure depends on the selected cooling strategy after forming. Cooling of the forged bevel gears in still air is insufficient to achieve operationally relevant hardness values. The required strength values might be achieved by quenching in water, but there is a risk of cracking in the cladded layer and an additional subsequent tempering operation would be required. By means of a process-integrated heat treatment, it is possible to adjust the required properties specifically. By application of such a treatment, consisting of a surface hardening with subsequent self-tempering from the residual component heat, coarse-grained structures, which have not been recrystallized due to different strains within the teeth of the bevel gear, can be refined. The heat treatment allowed for a partial or complete suppression of the intermediate layer between the base material and the coating material in the tooth tip, thus improving the material closure between the base material and the coating material and contributing to its homogenizing.

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