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ScienceDirect

Procedia Engineering 207 (2017) 884–889

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on the Technology of Plasticity, ICTP 2017, 17-22 September 2017, Cambridge, United Kingdom

Resource-efficient development of thermally highly resistant engine components of hybrid metal composites – experiments and numerical analysis

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Abstract

Requirements for protection of environment and climate, increasing energy cost and security demands form the basis for research activities in the maritime sector. Within the scope of the joint project »INKOV – development of innovative piston and valve solutions for composites in ship engines« metallic composites are developed and investigated. Their application in large engines powered by heavy fuel oil shall reduce nitrogen oxide emissions. The investigations of the publicly funded research project intend to generate high-strength components made of a hybrid composite material while simultaneously increasing resource efficiency. The focus of the research and development activities lies on components for large engines which are subject to extremely high dynamic, thermal and corrosive loads. Using conventional heat-resistant and wear-resistant steels, the wear related to the conditions of the application site can hardly be controlled. High-performance alternatives are necessary. The goal of the approach is to specifically apply a nickel-base alloy to a locally limited area by using a selected thermal joining process. Thus, a layer composite is to be produced, which corresponds to the solid material of a nickel-base alloy regarding its properties of thermal resistance and corrosion resistance. Currently, criteria for excluding the integration of these materials include high prices as well as their partly limited availability despite of their reported suitability for high-temperature applications. Using hybrid materials should open up their considerable potential in terms of increasing strength and high-temperature resistance while simultaneously reducing wear-related downtimes to a minimum. An aim of the project is to implement forming processes of hybrid composites by means of simulation as a basis for optimizations in terms of joining materials, joining processes or geometrical dimensions. Furthermore, the basic behavior of hybrid materials and their interface shall be examined in hot bulk metal forming by means of the generated FEM models.

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Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.
10.1016/j.proeng.2017.10.846

Keywords: hybrid composite material; resource efficiency; FEM; bulk metal forming

1. Introduction

Steadily increasing demands in functionality and environmental compatibility of current innovative materials continuously require new developments. For example, the conventional steels for high temperature applications have reached a very high level of development over the past years and have met their limits. Due to targeted combination of different materials, hybrid composite materials are at top of latest material developments. These materials allow integrations in areas where conventional materials alone do not meet the requirements any more. The use of optimized and feature-adapted hybrid composites leads to significant advantages regarding cost and weight compared to solid materials [1].

The focus of the research and development activities lies on components for large engines which are subject to extremely high dynamic, thermal and corrosive loads. Using conventional heat-resistant and wear-resistant steels, the wear related to the conditions of the application site can hardly be controlled. The goal of the approach is to specifically apply a nickel-base alloy to a locally limited area by using a selected thermal joining process. Thus, a layer composite is to be produced, which corresponds to the solid material of a nickel-base alloy regarding its properties of thermal resistance and corrosion resistance. Currently, criteria for excluding the integration of these materials include high prices as well as their partly limited availability despite of their reported suitability for high-temperature applications. Using hybrid materials should open up their considerable potential in terms of increasing strength and high-temperature resistance while simultaneously reducing wear-related downtimes to a minimum [2]. By specific utilization of the finite element method (FEM), the forming behavior of metal composites shall be illustrated and their specific properties shall be coordinated. Up to now FEM has been able to represent forming processes of hybrid composites only to a limited extent. The composites are characterized by a distinctive quality gradient of the materials and their geometrical dimensions. It is difficult to provide an exact definition of the joints and the suitable material parameters. An aim of the project is to implement forming processes of hybrid composites by means of simulation as a basis for optimizations in terms of joining materials, joining processes or geometrical dimensions. Furthermore, the basic behavior of hybrid materials and their interface shall be examined in hot bulk metal forming by means of the generated FEM models [1, 3, 10]. In the last years there has been an increased focus on temperature resistance in high performance materials. To be able to use components for raised application temperatures, there has been an increasing focus on metal-based hybrid composites. Numerous research projects are currently dealing with the fundamental production of composite materials. Since the basic feasibility of forming processes using metal composites was demonstrated, the specific composites were increasingly investigated [11, 12, 13]. Due to their properties in applications, high-temperature alloys have become the focus of investigations dealing with these properties [14].

2. Materials and experimental procedures

Today hybrid material composites are at the forefront of material developments. In the joint project, the focus lay on a composite of two metals, conventional heat-treatable steel and high-temperature alloy. The heat-treatable steel 42CrMo4, and the nickel-alloy René 41 were selected for the investigations. Both materials were fundamentally characterized concerning their chemical composition by means of a glow discharge spectrometer (GDOES) and by comparing them to the standardized values.

In order to effectively use a composite of the above-mentioned materials, adhesive bonding of the two materials is indispensable. This is advantageous for reasons of thermal conduction as well as regarding the construction. The resulting transition zone between the two materials must be ductile enough to remain free of any defects during the subsequent hot-forming process. The intended composite should occur due to a deposition of defined additional material in different layer thicknesses. Automated welding processes are particularly suitable in this regard. The weld deposit, which consists of the nickel alloy in the present investigation, is raised in beads in one or several layers. In the process itself a very fine-scaled surface is targeted to exclude forging errors already at the beginning. During the project the following methods were examined and their practical application was evaluated: gas tungsten arc welding (GTAW), gas metal arc welding – (GMAW), laser deposition welding and plasma-powder deposition welding (PTA). PTA-welding and laser deposition welding were detected as the most suitable welding processes. The PTA-welding process offers the opportunity of producing very wide welding beads, which limits the numbers of overlaps and generates a thick layer (up to 5 mm) in one single layer. In contrast, laser deposition welding allows for the generation of very fine beads. Thus the melting of the basis material can be regulated precisely via the energy input. The main focus in numerical analyses lay on the computational proof of the faultless formability of the thermally joined composites. The simulations considered the influence of the process parameters of temperature and strain rate on the forming result as well as the forces required for forming. The validation of the simulation results occurred in real-life tests. Finally, the microstructure of the materials was assessed as well as their forming behavior in compression tests. Moreover, the adhesive strength of the composites was evaluated for various specimen states by using shear tests (see figure 1).

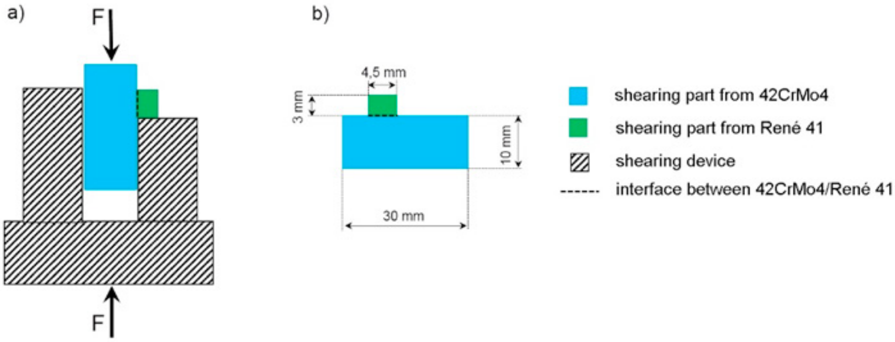

Fig 1 a) schematic illustration of the shear test b) geometry of the shear sample

In the further course of the investigations a suitable technology was to be found to increase the strength of the composites in spite of their extremely different routes of heat treatment. Forming simulations of composites require input values such as temperature, flow curves as well as acting thermal and mechanical loads. The investigations were carried out for modelling of the forming behavior of hybrid material components by using the simulation software *simufact.forming 13.3.1*. The software offers two solver technologies: the implicit finite element solver (FE, which we used and the explicit finite volume solver (FV). The finite element solver is an enhanced version of the MARC solver from MSC.Software Corporation. MARC was developed on the basis of the displacement method. The stiffness methodology used in MARC addresses force-displacement relations through the stiffness of the system. The materials and their connection to each other are of high priority in the numerical mode, since the behavior in the forming process shall be described as realistically as possible. Specific influences must be sufficiently considered such as temperature, strain rate and the behavior of the two metals towards each other. The material parameters of the used heat-treatable steel 42CrMo4 were selected from the deposited material database and assigned to the suitable base body. For the material of René 41 a material description was used based on the dates of Pan et al. [4]. The modelling of the coating was simplified by means of an adhesive condition between the two materials. This condition excludes the separation of the two materials. The friction between the composite and the tools was set at a coefficient of friction of 0.12, which is standard for forging processes [8]. The heat used during the forming process has a significant influence on the material properties and consequently on the result of the forming process. Therefore the used materials and their joined connection shall be exactly defined in order to achieve a real representation of the forming process, if possible. The definition of the heat transfer between René 41 and 42CrMo4 is based on the assumption that the composite behaves like a single semi-finished product with adhesive bonding. The coefficient of thermal conductivity is a proportional factor which depends of the used material and the temperature. For the numerical simulation an optimized heat transfer was necessary, so that the heat transfer coefficient must be described for the compound. The coefficient constitutes a specific ratio for the depth of the heat transfer along the interface. Based on the acceptance of a minimal interface a local coefficient was calculated from the equation [9]:

$$\alpha = \frac{\lambda}{\delta} \quad (1)$$

A high coefficient of heat transfer was selected corresponding to publications relevant for the project. In the case of the present composite system, an approximate flow behavior could be identified at a steel carrier temperature of 900°C and a temperature of 1050°C for the nickel alloy. Consequently a model was developed in which a temperature gradient could be generated in the composite component. Against this background two possible heating concepts (induction heating, furnace heating), were investigated by means of numerical simulation. Placing the focus on later practical implementations, the attention of the investigations was primarily concentrated on inductive heating. In the used simulation software inductive heating is not integrated, in contrast to a heating by means of a furnace which is a stand-alone tool. An electrical magnetic thermal mechanically coupled analysis would have to be carried out, which the software does not allow. In order to handle this obstacle, the possibility to simulate such heating consists in simulating heat conduction from a hotter component to a cold one. Both heating methods have been analyzed using basic experiments examining the forming behavior, and by utilizing the chosen demonstration unit. Compression tests (axial) in form of a two-dimensional simulation model were used for basic experiments of the general forming behavior of hybrid composite materials. All assumptions and parameters for the basic model were applied for the investigation of the forming behavior of the demonstration unit. In order to crosslink the semi-finished composite, Overlay Hex-Mesh was used, which is integrated in the software. An element edge length of 0.5 mm was chosen for the Overlay Hex-Mesh. At the beginning of the investigation a temperature of 900 °C was assumed for 42CrMo4 and a temperature of 1050 °C was assumed for the nickel alloy. These assumptions were based on the flow curves. A tool temperature of 100 °C was assumed for the compression tests. A specific strain rate was chosen ensuring that it could easily be used for later experiments (10 mm/s).

3. Results and Discussion

Components made of hybrid material composites require specifically adjusted and optimized steps for the production of a faultless and adherent composite, which allows defect-free forging and further processing. Extensive test series investigated and evaluated the properties of the composites which had been produced by various methods. Based on the results from the basic experiments, demonstration units were produced, which were verified to be suitable high-performance engine components. In particular, the following results were determined. A first characterization of the composite was carried out after the welding. This characterization included an investigation by means of GDOES. It was revealed that considerable variations were created in the chemical composition of the nickel alloy René 41 after deposition welding. These variations can be explained by the peculiarities of the PTA-welding process. Due to the low layer thickness of the applied alloy and the high welding current of 170 A, strong melting of the basis material occurs as well as blending of basis and filler material. For this reason, e.g. the share of iron in the layer is clearly higher than in the initial powder. In the further course of the project the mechanical properties of the layer were determined for various states. In the first step a compression test was applied. The 0.2 percent compression limit was merely 540 MPa (blue) at 20 °C using René 41 in the welded state In a subsequent forming step, the compression limit was increased to 660 MPA (orange). A heat treatment turned out to be even more effective. Thus, the values of the ascertained compression yield were raised to 740 MPa (grey). Further increase was achieved by combining forming and heat treatment. Using this test series resulted in maximum values of 870 MPa (yellow). In order to characterize the material behavior under conditions comparable to the intended specific application, the same experiments were carried out using a temperature of 500 °C. These experiments demonstrated the importance of an effective heat-treatment. In both the welded state as well as the welded and forged statewithout appropriate heat treatment the compression limit decreases to 440 MPa or to 480 MPa at a compression temperature of 500 °C. Applying the heat treatment maintains the opposed strength level even at increased temperatures. The reason for this behavior lies in the formation of temperature-resistant precipations (γ′) during the heat treatment process. When comparing the compression limits of the basis material to those of the nickel alloy at 500 °C, it is justified to use the superalloy as surface layer. The green bar (figure 1) shows the effects of the compromise of different heat-treatments of the steel and the nickel alloy on the compression limit The yield stress at 20 °C was increased to 810 MPa and at 500 °C it was raised to 730 MPa. A slight loss of high-temperature strength shows that the heat treatment parameters for the nickel alloy are not quite optimal. Nevertheless, the high-temperature strength is very high.

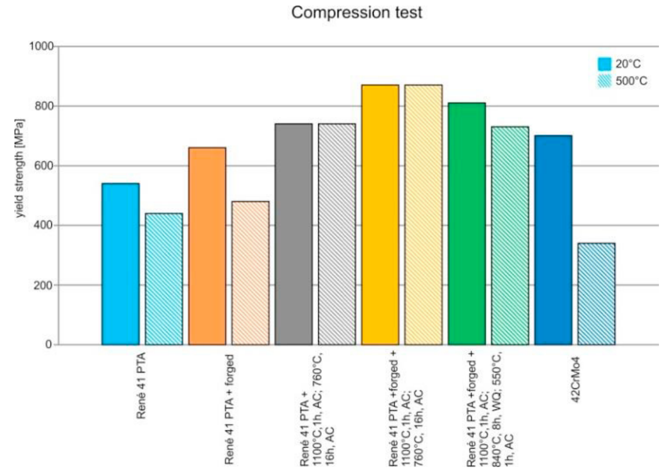

Fig. 2: Influence of the heat-treatment on the yield strength

However, it is necessary to consider the tempering stage of the steel as demonstrated in the determined values of adhesive strength. Shear tests were performed to determine the adhesive strength of the composite in the different states, similar to those in the compression tests. After PTA-welding the adhesive strength of the surface layer amounted to 550 MPa. Due to forming of the composite the adhesive strain was increased to 600 MPa. The subsequent heat-treatment, which would be optimal for the nickel alloy, has a negative effect on the adhesive strength, so that values of only 510 MPa were determined. If the optimized heat treatment regime is applied to the metal composite, the adhesive strength can be increased to 720 MPa. The high strength after the optimal heat treatment is caused by the high hardness of each composite partner. The hardness of René 41 amounted to 330 HV 10 and that of 42CrMo4 amounted to 300 HV 10. Thus, the composites also exhibit high and similar hardness values. When the heat treatment regime for the nickel alloy was optimal, hardness values of 352 HV 10 were achievable; however, the hardness of the steel fell to 184 HV 10 at the same time, so that the entire composite lost adhesive strength. The characterization of the forming behavior of the composite was carried out in compression tests. The input parameters for the FEM modelling of the process were almost identical to the parameters adjustable in the experiments. Nevertheless, in the real experiment the specimen could be heated only to a uniform temperature. In contrast, in the simulation a temperature gradient was defined between the two metals, which guaranteed optimum forming properties for both materials. The focus of the experiments lay on verifying the appearing geometry of the reshaped specimen. The experimental results of both variants are close to each other. In spite of the same friction conditions in the header die, the steel formed around the nickel-alloy of the surface layer. The reason for this phenomenon lies in different materials and their various yield stresses at a specified forming temperature. By using tracking individual elements during the forming process, the diverse material behavior can be graphically represented by means of numerical simulation. High correspondence was established when comparing the real component manufactured by forming, the piston head, with the results of the FEM simulation. Hardly any deviations were recognized in the wall thickness of the additional material (see figure 3).

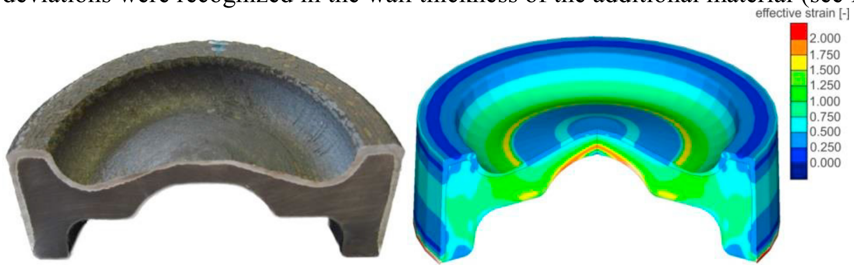

Fig 3: Comparing of the real component manufactured by forming with the results of the FEM simulation

Merely at the bottom edge low differences appeared between real component and simulation. If the additional layer is distributed evenly on the circumferential surface in the numerical simulation model, tapering of the layer thickness appears in the real component shortly above the bottom edge. The surface quality of the forged piston heads was sufficiently high for the resulting components after machining to comply with the requirements.

4. Conclusions and prospects

The study presented in this article was carried out with the aim of evaluating, from an environmental standpoint, the developing and processing of hybrid metal compounds. The core issue of the cooperative project "INKOV" consists in developing engine components resistant to high dynamic and thermal loads by applying special metal hybrid composites, which comply with the requirements of future generations of large engines. Environmental issues are of major concern. Previous investigations show that hybrid composites can meet the future requirements for components used in large engines powered by heavy fuel oil, when considering all technological process parameters in deposition welding, in heat-treatment prior to forming, during forging and in the defined post-heat-treatment. Furthermore, it was demonstrated that forming simulations represent a versatile tool for basic analysis of the composite conditions. Thus areas of critical stress and strain can be determined and possible areas of failure can be identified. Using the simulation software *simufact.forming 13.3.1*, an appropriate strategy was developed to represent forming processes of hybrid material composites. These representations were close to reality. As a result statements can be made regarding the flow behavior of each material. Furthermore, the achieved deformation levels can be detected for specific points. The conducted experiments correlate with the simulation results. Consequently, at an early development stage the numerical simulation of the process allows a statement regarding the forming results and expected properties. In the course of the investigation, the demonstration unit (piston head) shall be joint and finished with the piston skirt. In terms of thermal fatigue resistance, long-term tests shall be performed on test benches for engine and corrosion under practice-oriented conditions. In a current context of environment production and resource protection, the use and advancement of hybrid compounds may become distinctive element and a source of competitive advantage to be exploited.

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