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Approach for a sustainable process chain in manufacturing of fasteners for mechanical joining

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Abstract. With regard to environmental protection, the sustainability of production processes is decisive. Mechanical joining technologies like self-piercing riveting are of special importance with regard to realising lightweight constructions in the automotive industry. However, the production of self-piercing rivets is costly, time-consuming and energy-intensive, as the rivets conventionally must be heat treated and coated in order to ensure an adequate strength, ductility and corrosion resistance. Within this paper, it is shown by the example of a newly established rivet manufacturing process how the sustainability of fastener production can be increased. The general approach in this context is the use of alternative, high strain hardening stainless steels as rivet material, which allows the omission of the post treatment of the rivets after forming. The shortening of the process chain enables a more sustainable rivet production. Thus, not only the energy consumption is reduced, but also costs, which is why the novel manufacturing process is also of interest from an economic point of view.

Introduction

The protection of the environment and the natural resources as well as the tackling of climate change are challenging issues for the manufacturing industry. Hence, new industrial solutions that enable a reduction of CO_2 emissions and energy consumption have to be found [1]. To reach a reduction of emissions in car traffic, the lightweight design of car bodies is an established method. The lightweight design causes an increasing use of multi-material structures made of high-strength steel and aluminium. To join these materials the use of mechanical joining techniques like the self-piercing riveting (SPR) is emerging [2]. The process stages of SPR and the characteristic joint parameters are shown in Fig. 1.

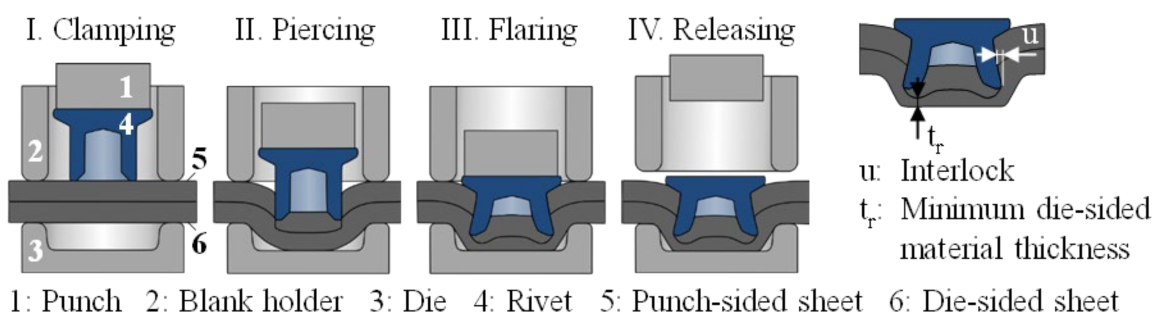


Fig. 1. Characteristic of the SPR process according to [3].

The rivet is pressed into the clamped sheets and pierces the punch-sided material. After that, the rivet flares and an interlock is created within the die-sided sheet. The interlock is the most important property of the joint, because it is an indicator for the expectable joint strength [4]. The joining result depends on the rivet and the die, which are selected in accordance to the strength, the ductility and the thickness of the sheets to be joined [5]. Rivets for SPR differ in geometry, material and the surface condition. As a function of the materials used for car bodies, several different rivet geometries were developed in the past. Due to the challenges when joining high-strength steel, especially on the die side, the authors have designed a new rivet geometry for the joining of two challenging material combinations consisting of high-strength steel HCT780X and aluminium EN AW-5083 in former studies [6]. Based on this rivet geometry an innovative rivet with special properties and a completely new approach of the rivet manufacturing process are developed, as explained within this paper.

Approach for a sustainable process chain

A holistic view of the process chain related to SPR refers not only to the joining process itself, but includes the entire life cycle from the material production process to the use of the finally joined components, as illustrated in Fig. 2. There is a great potential to improve the process efficiency and sustainability of the rivet manufacturing process in particular.

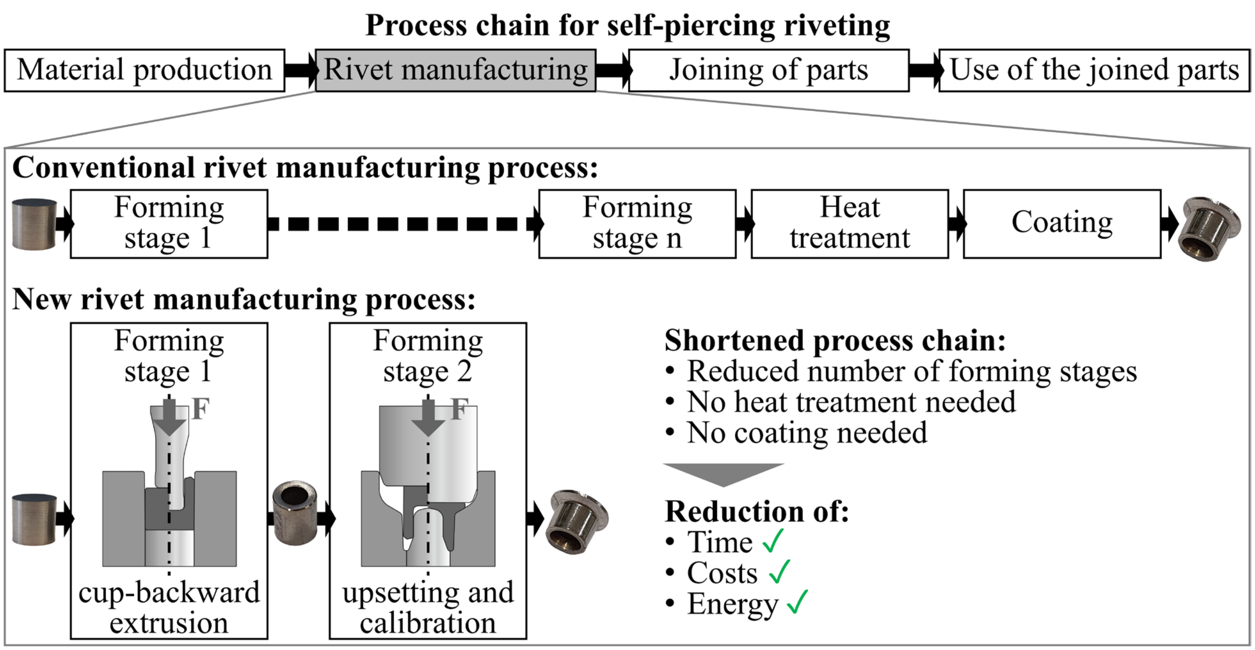
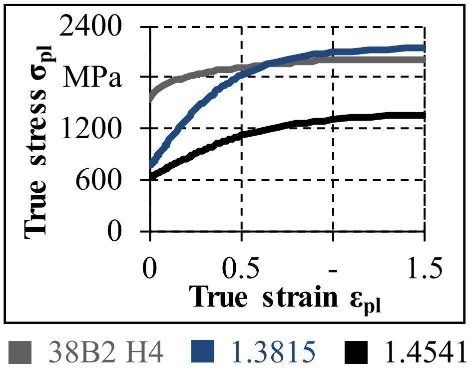


Fig. 2. Entire SPR process chain and comparison between new and conventional rivet manufacturing process according to [7].

Rivets are generally made out of high-strength boron steels [5] and are formed in multistage cold forming processes [2]. To ensure an adequate strength and a good corrosion resistance, the rivets must be heat treated and coated after the rivet forming process [8], which makes the entire rivet production time-consuming, energy-intensive and costly. Especially the heat treatment process, more precisely the hardening and tempering of the rivets, is energy-intensive. Unfortunately, the authors have no insight into the energy and cost structure of the manufacturing companies. This is why only a qualitative evaluation with regard to the rivet manufacturing process is possible. However, it is known from [9] that about 40 % of the energy that is used in the industrial environment in Germany is attributed to heat treatment processes. This is underpinned by the results of a scientific analysis carried out by Mendioka et al. [10] concerning the energy consumption of a steel foundry, which reveals that more than a third of the total gas of the company is consumed due to the heat treatment. As a logical consequence, there is a need to avoid the heat treatment of cold formed components. Considering in addition the wide use of mechanical joining operations and the rising energy prices, a more sustainable and economical rivet manufacturing process is needed.

The approach presented in this paper relates to the shortening of the rivet manufacturing process chain by eliminating the need of the post treatment of the rivets in order to increase the process efficiency and the sustainability. The key aspect for this is the use of high strain hardening stainless steels as rivet material. An overview of a selection of potential rivet materials is given in Fig. 3.



Material	Mass fraction of chemical components [m%]						
	C	Mn	Cr	Ni	Ti	B	N
38B2	0.38	0.76	0.27	X	X	0.004	X
1.3815	0.08	18.86	17.07	0.58	X	X	0.76
1.4541	0.02	1.55	17.14	9.19	0.27	X	X

Fig. 3. True stress - true strain curves and chemical composition of new rivet materials in comparison with conventional rivet material 38B2 according to [3].

In the context of the material choice, high nitrogen steels such as the featured steel 1.3815 represent a promising option. The chosen material 1.3815 is an established high nitrogen steel, which was already used for highly stressed retaining rings for turbo-generators due to its excellent material properties [11]. Steels of this type are characterised by an exceptionally high nitrogen content and provide a high strength, ductility and corrosion resistance [12]. Due to the high strain hardening, a sufficient rivet strength for joining can already be achieved through the forming process. Therefore, the usual heat treatment and coating of the rivets becomes obsolete leading to cost, time and energy savings. Thus, the benefits of forming as an efficient and sustainable technology are fully exploited. Furthermore, the comparison between the conventional and the new process in Fig. 1 also reveals that the new process consists of two forming stages in contrast to the usual up to six stages in industry. Consequently, energy and costs required for the manufacture of additional forming tools including the tool materials can be saved. It must be pointed out that the production of materials such as high nitrogen steels involves more expenditure compared to conventional steels, which is opposed to the cost and energy savings by omitting the heat treatment and the coating. There is a need for future research and development in relation to the material production processes in order to exploit the potential for energy and cost savings in this field as well. Nevertheless, the new approach contributes to an increase in economic efficiency and sustainability of the rivet manufacture. As SPR is used in the automotive sector in particular, this is also an important step on the way to fully sustainable mobility in the future, because the production history of each individual vehicle component counts in this case.

Forming of Rivets with Graded Mechanical Properties

The new rivet manufacturing process, as presented by the authors in [7], consists of two forming stages, cup-backward extrusion in stage 1 in combination with the forming of the rivet head and foot in stage 2. The mechanical properties of rivets, besides the rivet geometry, are decisive for the joining process and for achieving an adequate joint formation. This applies in particular to challenging joining tasks such as the joining of high-strength steels on the die side. The hardness analysis of the new rivets made of 1.3815 (Fig. 4a) reveals that over the whole rivet cross section a mean hardness of about 600 HV 0.02 is reached. Thus, the hardness range of conventional rivets made of boron steel, which is 480 HV ± 30 HV in the heat treated condition [6], is not only completely covered, but even extended by the new rivets manufactured without heat treatment.

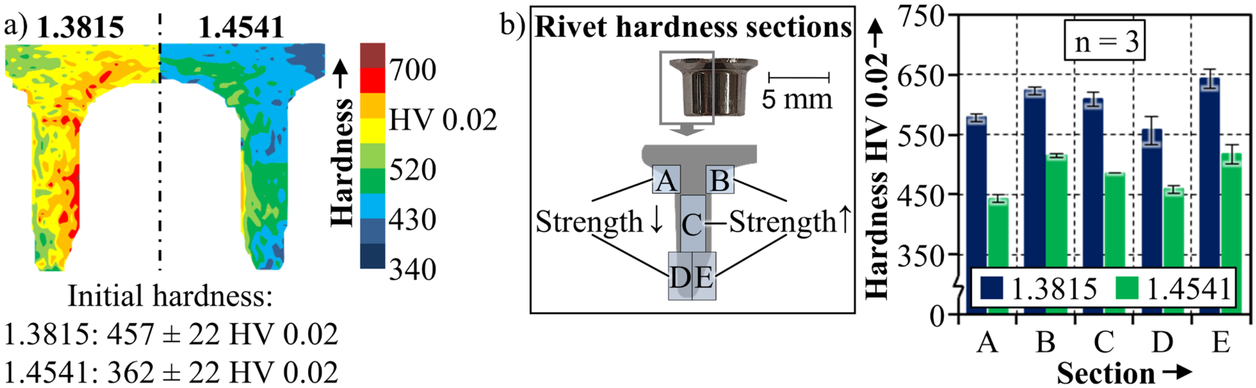


Fig. 4. a) Rivet hardness after forming according to [7] and b) Local hardness in dependence of the selected rivet sections.

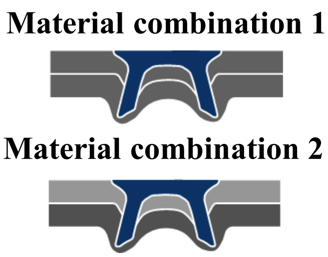
A particular potential of the new rivet manufacturing process lies in the fact that the hardness gradation after forming remains intact in contrast to conventional heat treated rivets exhibiting homogenous mechanical properties. This provides the chance to specifically adapt the hardness according to the requirements during the joining process, either by selecting different forming sequences or by replacing the rivet material. In this case, the presented two-stage forming process is chosen in order to create a beneficial hardness distribution with regard to the special requirements arising in particular when joining high-strength steels. This results in varying hardness values in different rivet sections, as depicted in Fig. 4b. Inside high-strength materials the flaring process is problematic [5]. The interlock formation that is essential for the joint formation and the resulting joint strength is influenced by the flaring. A too low flaring can be the reason for an insufficient interlock. Against this backdrop, the achieved hardness gradation of the new rivets is advantageous. For joining with conventional rivets, a risk for the occurrence of cracks in the transition area between the outer rivet shank and the rivet head in particular was found in [6]. In addition to the high ductility of high nitrogen steel, which is even maintained for high strains, the comparatively lower hardness in section A is beneficial before the background of the risk of cracks. In accordance with this assumption, no cracks after joining using the new rivets made of 1.3815 could be found. To avoid the excessive deformation of the rivet shank, what is known to be a high risk when joining high-strength steel [2], the sections B and C are characterised by a relatively high hardness. The mean hardness in the outer area of the rivet foot, section D, is lower compared to the hardness in section E and thus facilitates the rivet flaring and the interlock formation. Moreover, the comparatively high hardness in section E ensures that the foot chamfer is not deformed while cutting the upper sheet, especially in case of using high-strength steel on the punch side, because the chamfer is important for the subsequent beginning of the flaring. Thus, the gradation of the rivet hardness can be used to support the joining.

The results of the hardness analysis for another potential rivet material, the stainless steel 1.4541, are also shown in Fig. 4. As the initial hardness and the strain hardening of 1.4541 differs from the high nitrogen steel 1.3815, different hardness levels are achieved in dependency of the material. The transferability of the approach demonstrates the potential for manufacturing a wide range of rivets with graded mechanical properties, which can be set depending on the requirements of the joining process. This enables the production of customised rivets to realise joining processes, which are not possible using conventional rivets.

Joining of High-Strength Materials

The use of a new rivet material provokes some issues for the joining process. One benefit of the corrosion resistance of the new rivet material is that the coating can be omitted. However, it is known from [13] and [14] that the surface conditions of the rivet and the sheets have an influence on the friction between the rivet and the sheet materials during the joining process. Because of the changed friction properties, the rivet deformation and the generation of the interlock are affected. However, a study concerning the influence of the rivet surface condition came to the finding that the friction influence is limited and especially the friction properties of uncoated rivets and rivets plated with the common coating Almac® are very similar [3].

As stated at the beginning, the new rivet is designed for the joining of material combinations consisting of high-strength steel and aluminium to cover a wide and relevant range of joining parts. The validation of the approach is conducted for the material combinations specified in Fig. 5. For the comparison to a conventional rivet, the rivet type from [6] is used. This rivet has a geometry, which fulfils the requirements of both material combinations. It is made of boron steel 38B2 and quenched and tempered to a hardness level of 480 ± 30 HV. The surface is coated with Almac®.



Material	Sheet thickness (mm)	Yield strength YS (MPa)	Tensile strength TS (MPa)
■ HCT780X	1.5	564.1 ± 2.2	860.8 ± 1.3
■ EN AW-5083	1.5	157.3 ± 1.0	291.5 ± 0.6

Tensile test; n = 5; rolling direction = 0°

Fig. 5. Material combinations and mechanical properties of the sheet materials to be joined.

The comparison between the conventional rivets and the new type of rivet made of 1.3815 and 1.4541 is initially made by evaluating the rivet deformation and the joining results based on multi-step joining tests. In the cross-section of the joints, the deformation of the rivets can be analysed within the different process stages (Fig. 6). Due to geometrical deviations of the rivets made of 1.3815 and 1.4541 compared to the target geometry that are caused by the forming process, the rivet head diameter is much lower than with conventional rivets. Further deviations are existing within the rivet foot. However, the geometrical deviations do not impede the joining process. Instead, it can be demonstrated that the joining result with rivets made of 1.3815 fulfils the common quality criteria of [4] and that the new rivet has a competitive joining performance compared to conventional rivets. In addition to the examination of the geometrical deformation of the rivets, the hardness within the rivets is measured for each step so that the change in the material condition can be analysed, too. As the material condition is almost homogenous within the conventional rivet, due to the heat treatment, the material hardness within the new rivet type is locally different. In the first process step, the initial hardness distribution is still existent. Compared to the conventional rivet, the hardness within the outer rivet foot is lower than with the rivet made of 1.3815. Nevertheless, as the hardness within the conventional rivet increases by approx. 15 % during the joining process, the increase of the hardness within the rivet foot of the rivet made of 1.3815 is much higher and at the end of the process a comparable hardness is reached. The hardness distribution within the rivet made of 1.4541 is similar to the hardness distribution within the rivet made of 1.3815, but the hardness level is much lower. The lower material strength of 1.4541 causes the compression of the rivet and no joint can be created. Therefore, it can be seen, that the rivet material strength has a significant influence on the deformation behaviour of the rivets and the joining result.

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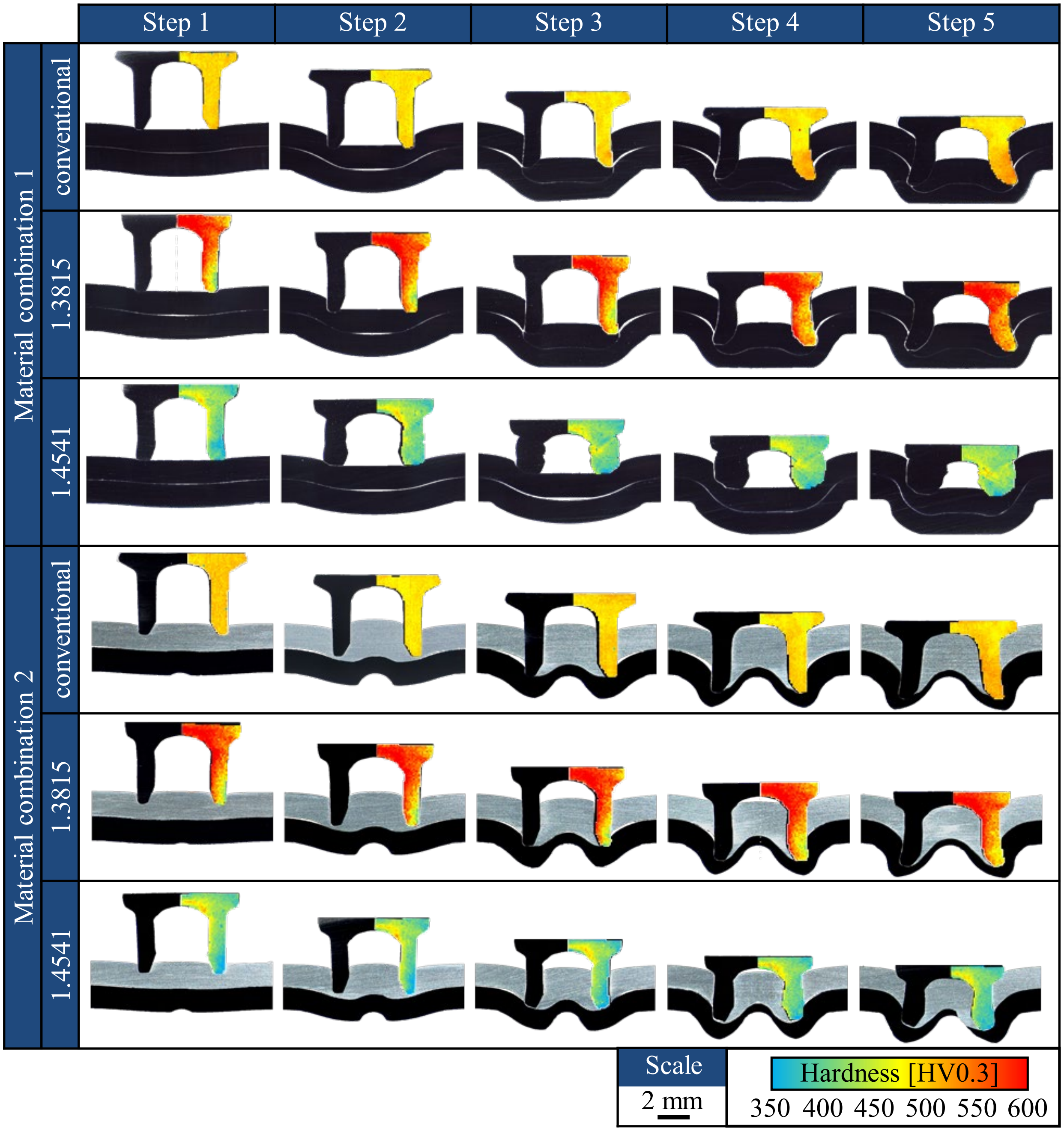

Fig. 6. Joining result with conventional rivets and rivets made of 1.3815 and 1.4541 in accordance to [3].

However, as the competitive joining of the two material combinations with rivets made of high nitrogen steel 1.3815 could be proved by the illustrated joining tests, the joint strength has to be determined, too. Therefore, in [15] the strength of joints riveted with conventional rivets and rivets made of 1.3815 was analysed by experimental tests. Tests under quasistatic load were conducted. The reached maximum force until failure of the joint and the kind of failure were evaluated. By doing so, it could be found that the smaller rivet head diameter of the rivets made of 1.3815 provokes a lower joint strength of approx. 25 % when testing material combination 2. The punch-sided aluminium sheet is teared over the rivet head at a reduced force compared to a rivet with a bigger head diameter. Because of that, the elimination of the geometrical deviations of the new rivets has to be a goal of further research.

Summary and Outlook

As an approach for sustainable manufacturing, the potential of a novel rivet manufacturing process to save costs, time and energy is pointed out. The usually necessary treatment of the rivets after forming, including hardening and tempering as well as coating, can be omitted due to the use of high strain hardening stainless steel as rivet material. Thus, the entire process chain is shortened. Additionally, the new approach makes it possible to produce rivets with graded mechanical properties. This is a special feature compared to conventional rivets, which provide homogeneous properties due to the heat treatment. This opens up the opportunity of producing customised rivets with a varying local hardness. In this paper, the achieved hardness distribution of rivets formed from the high nitrogen steel 1.3815 and the stainless steel 1.4541 using the new rivet manufacturing process is discussed with regard to the requirements of the subsequent joining. Furthermore, the impact of the changed rivet properties on the joining process is assessed. In this way, a holistic evaluation of the process route is ensured. Material combinations of high-strength steel and aluminium alloy can be successfully joined with the new rivets. Nevertheless, it must be stated that the geometrical deviations of the rivets must be reduced in order to ensure an adequate joint strength. Therefore, future work will focus on the further development of the tool concept and on improved forming strategies to extend the existing process limits due to the high tool loads. Further research regarding tailored mechanical rivet properties will be conducted as well to improve the performance of riveted joints. In the future, the approach can be transferred to various fastener production processes to reduce energy consumption, costs and time. This contributes to a reduction of emissions and the protection of natural resources, which is an important factor for the increase in economic efficiency ensuring the competitiveness of manufacturers.

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