Reduction of Nickel-Alloyed Stainless Steels in Automobile Systems by Laser Beam Welding of Austenitic-Ferritic Connections While Maintaining an Adequate Corrosion Resistance

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Abstract. Nowadays mostly austenitic stainless steels, which are alloyed with the element nickel, are used for applications with demanding requirements concerning the chemical properties and corrosion resistance. Therefore in current automobile systems in the mid-range and premium price segment the exhaust piping is normally made of nickel-alloyed stainless steels, see figure 1. With regard to modern mobile systems, such as automobiles powered by hydrogen fuel cells and alternative liquid propellants nearly all components for the storage, transportation and chemical reactions are made of nickel-alloyed stainless steels. These types of steels typically feature an excellent chemical and thermal performance, which is often not necessary for the whole system. Thus quite a huge amount of nickel is wasted at installation positions and area of operation not requiring that high chemical persistency. For such installations with lower demands on the corrosion resistance also nickel-free ferritic stainless steels could be used. In order enable a reduction of the nickel-alloyed materials by ferritic variants without a decrease of chemical performance in the connection an appropriate joining strategy has to be engineered. In this context the present article presents the latest results of a research project dealing with austenitic-ferritic stainless steel connections performed by laser beam welding. By a reduction of nickel both economic as well as environmental improvements can be reached: On the one hand the high and also fluctuating market price of nickel leads to notably rising prices of nickel-alloyed steels, for which reason nickel-free variants offer cost savings up to 40%. On the other hand there is reasonable suspicion that the element nickel is carcinogen caused serious damage to the health of human beings, hence nickel should also be avoided as far as possible for this reason.

1 Introduction

For many automobile applications with higher corrosive loads, such as exhaust pipes in current cars, see Figure 1, or components for the storage, transportation and processing of alternative liquid propellants in modern mobile systems, so-called austenitic stainless steels are used. These materials generally feature excellent forming and welding characteristics [2] and are resistant against diverse chemical substances [3]. In order to realize such an austenitic microstructure, steels are primarily alloyed with the element nickel. Besides the stabilization of the cubic-face-centred austenitic grain structure nickel increases the corrosion resistance of a stainless steel in non-oxidizing acids. In contrast to the advantageous effect on the chemical stability, an alloying with the expensive element nickel leads to a significant price increase of the relevant steel type, see Figure 2.

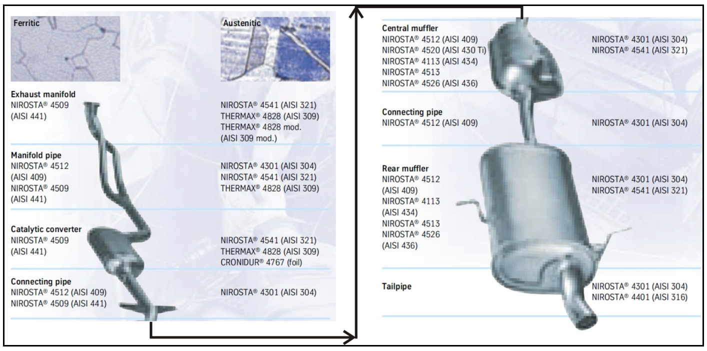

Fig. 1. Combinations of ferritic and austenitic stainless steels for exhaust systems of present mid-range and premium price segment automobiles. Left hand side: Ferritic steels, right hand side: austenitic steels [1].

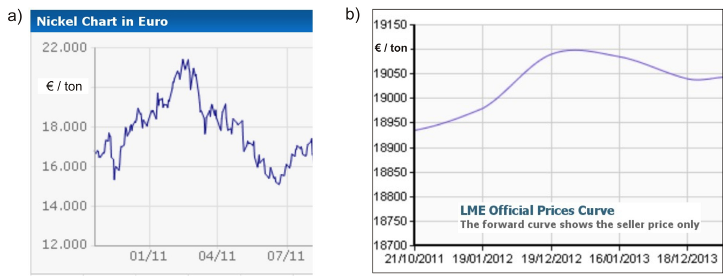

Fig. 2. Market price of nickel: a) Current situation [4], b) forecast for the next years [5]

According to Figure 2.a) nickel is on the one hand a comparatively expensive metal with a high average price of more than 18.000 € per ton and on the other hand its market price shows distinctive fluctuations. Both aspects are unfavourable for cost efficient fabrications, cost calculations of corresponding assemblies and the sale of the final products. In view of the future conditions, figure 2.b) shows a forecast of the price trend for nickel within the next years by the London Metal Exchange (LME). Thus the average market price is supposed to increase furthermore, up to more than 19.000 € per ton at the end of 2012. Consequently a reduction of nickel-alloyed steels is a very promising approach for cost-effective and steady-price constructions in the automotive engineering. In addition to these economic advantages, a downsized use of nickel-alloy steels also prevents the welding and cutting operators from perpetual and excessive exposition by nickel oxides, such as NiO, NiO_2 and Ni_2O_3, which typically occur at laser deep welding of CrNi-steels. New medical studies demonstrate that a long-term contact of human beings with nickel oxides effectuates the generation and growth of tumour, cancer and further remote health damages [6]. Therefore less nickel in the production of current and future automotives is also a sustainable practice to keep the welding personal's health.

For both implied reasons more and more industrial companies endeavour to introduce nickel-free stainless steels in their production, wherever possible. As installations points with very high demands on corrosion resistance can only be realized with austenitic steels, so-called tailored constructions with adapted material properties integrated at the particular assembly-position are designed [7]. For an implementation tailored constructions austenitic and ferritic stainless steels have to bee joint by metallic continuity and especially welding. Laser welding offers fast processing and low heat input, which allows joining thin-walled steel parts at negligible thermal deformation. However laser-welded combinations of austenitic and ferritic stainless steels without any optimization arrangements often results in the formation of local corrosion under demanding chemical loads, compare Figure 3.

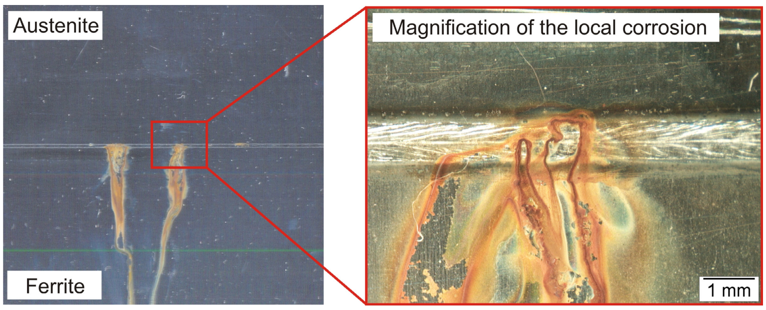

Fig. 3. Local corrosion at laser-welded austenitic-ferritic steels after salt spray test of 16 hours [Bavarian Laser Centre].

Local corrosions as seen in figure 3 are usually restricted to small areas of the weld zone, while the bigger part of the connection area is absolutely free of corrosion. However these comparatively small defective areas limit the implementation of such austenitic-ferritic joints up to now.

In order to prevent a local corrosion and enable a reduction of nickel-alloyed stainless steels, the possible causes for such punctual failures under chemical load have been analyzed at the Bavarian Laser Centre. The corresponding investigations highlighted, that local corrosion is particularly effectuated by non-uniform element intermixture in the melt pool, see Figure 4.

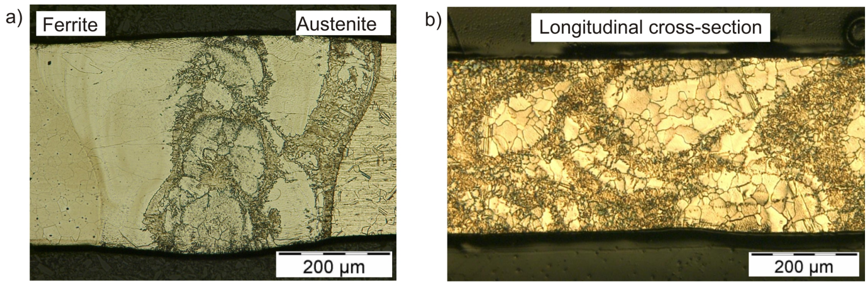

Fig. 4. Non-uniform element intermixture in the weld zone of austenitic-ferritic connections [blz]: a) Lateral cross-section, b) Longitudinal cross-section in the middle of the weld zone [blz]

While the external geometry of laser-welded austenitic-ferritic joints appears very constant, the welding process leads to a non-uniform distribution of the alloying elements of the relevant steels. Figure 4.a) shows a lateral cross-section of such a joint and demonstrates the irregular intermixture in the weld zoned. In addition Figure 4.b) reflects a longitudinal cross-section in the middle of a laser-welded connection, evincing a considerable turbulence coming along with highly ferritic zones, that tend to form coarse grain areas. Coarse grains lead to a decrease of the chemical and also mechanical performance of the welds, especially when there are conglomerates extending from the top of the weld to the bottom, compare Figure 4.b).

In order to significantly enhance an intermixture at the molten state and thereby obviate the formation of spaciously coarse grain areas, the present article discusses the use of filler materials and their effect on the chemical performance of welded connections. Although the handling of filler wires complicates laser welding processes and increases the costs for the welding procedure to certain extend, this process variant seems to be adequate to clearly improve the chemical robustness of laser-welded austenitic-ferritic connections at stainless steels. If in this manner a large-scale replacement of nickel-alloyed steels could be realized without decreasing the corrosion performance, overall an economic and environmental benefit is possible.

Hence experimental welding trials have to be set up and performed, dealing with the reproducible production of laser-welded thin-sheet connections with filler wire at high feed rates. After developing a stable joining process, the metallographic, chemical and mechanical characteristics of the welds have to be analyzed. Finally the question, whether a formation of local corrosion can be prevented shall be clarified.

2 Experimental Setup

For the experimental welding trials a continuous-wave disc laser from Trumpf is used. This Yb:YAG solid state lasers features a maximum output power of 4,0 kW at a wavelength of 1.030 nm and a focal diameter of 600 µm. Considering the stainless steels, samples with a dimension of 150 mm x 50 mm x 0.5 mm (length x depth x thickness) are cut out of metal sheets by means of laser cutting. The material data of the considered austenitic and ferritic stainless steels is given in Table 1. As austenitic chrome-nickel steel the 1.4301 is used, as this steel is the most prevalent applied austenite in Europe. On the ferritic side two materials, the 1.4016 and the 1.4520 are contemplated. 1.4016 is only alloyed by chrome and features a market price of about 40% less than 1.4301. Because of the extensive formation of coarse grain of 1.4016 during thermal welding also the titanium-stabilized 1.4520 is analysed. By means of stabilization, coarse grain zones within the weld can be prevented.

Table 1. Material data for the considered austenitic and ferritic stainless steels.

Microstructure	Material-Code acc. EN10088-2	Material-Code acc. ASTM	Chemical composition
Austenitic	1.4301	304	X5CrNi18-10
Ferritic	1.4016	430	X6Cr17
	1.4520	-	X2CrTi17

These types of stainless steels with the implied plate-thickness of 0.5 mm are connected in a butt-weld configuration. For this purpose a clamping device is designed, which allows a reproducible positioning of the samples in a zero-gap constellation. First the austenitic and ferritic sheet metal samples are locked into position by clamping plates, compare Figure 5. Then an adjustable screw can be operated to assure a zero-gap between the samples. The position of the joining area relative to the laser system is given by an appropriate dead stop of the base structure of the clamping device.

For the supply of additional alloying elements and an enhancement of the intermixture in the molten state, a filler wire made of the austenitic steel 1.4576 (ASTM: 318Si, X5CrNiMoNb19-12) is also inserted into the weld zone. Here the wire diameter is set to 0.8 mm, as this is a commonly used and goo available wire, which can be manipulated by all standard wire feeding systems. All the experimental trials are performed under pure Argon shielding gas, which is injected as well from the top as the bottom side of the weld.

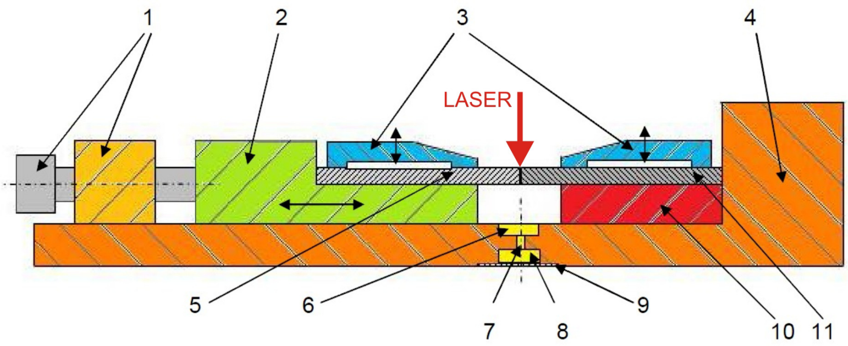

Fig. 5. Clamping device for the experimental welding trials [Bavarian Laser Centre].

3 Welding Test Results

During the experimental trials it can been seen, that reproducible welds at 0.5 mm sheet metal samples with a 0.8 mm filler wire are achievable with adapted parameters. Too slow process feed rates of less than 3 m/min lead to an immoderate heat input and thereby an excessive formation of coarse grains at both considered ferritic materials. On the contrary, process feed rates of more than 7 m/min require immoderate high laser powers, so that a lot of splatters and melt emissions occur. For all analyzed materials a feed rate of both the process and the filler wire of about 5 m/min lead to the best results and can be recommended. In figure 6 an example of a connection of 1.4016 and 1.4301 demonstrates the feasibility of the implied connections and shows a comparatively balanced element intermixture in the weld zone.

In comparison of welds with the non-stabilized ferritic steel 1.4016 and Ti-stabilized ferritic steel 1.4520, a distinctive formation of coarse grain in the heat affected zone of 1.4016 can be noticed, see Figure 7a). On the contrary an alloying with less than 1 mass-% titanium in case of 1.4520 inhibits an excessive grain growth, compare Figure 7b). As the price difference between materials stabilized and respectively not stabilized with titanium amounts less than 10%, this kind of alloying has to be recommended in order to prevent a mechanical and chemical degradation of the stainless steel connections after laser-welding.

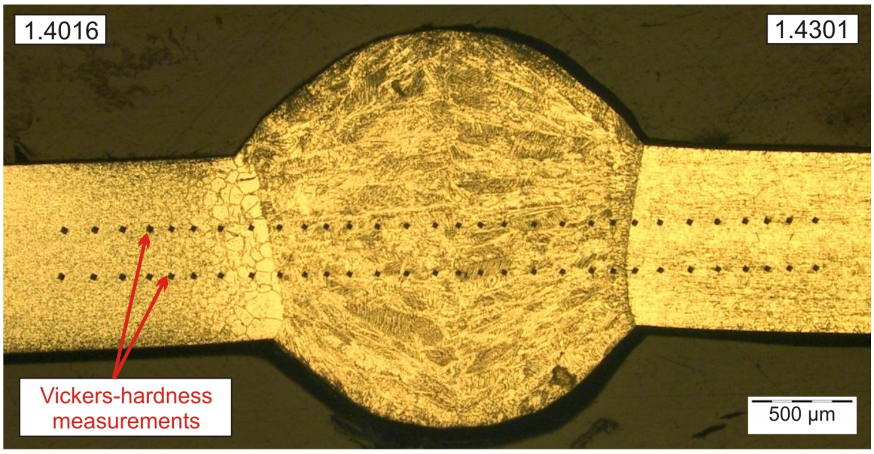

Fig. 6. Lateral metallographic cross-section of a austenitic-ferritic weld of 1.4016 und 1.4301, welded with continuous-wave solid-state laser and filler wire 1.4576 (laser power 2.800 W, process feed rate 5 m/min, wire diameter 0,8 mm, wire feed rate 5 m/min).

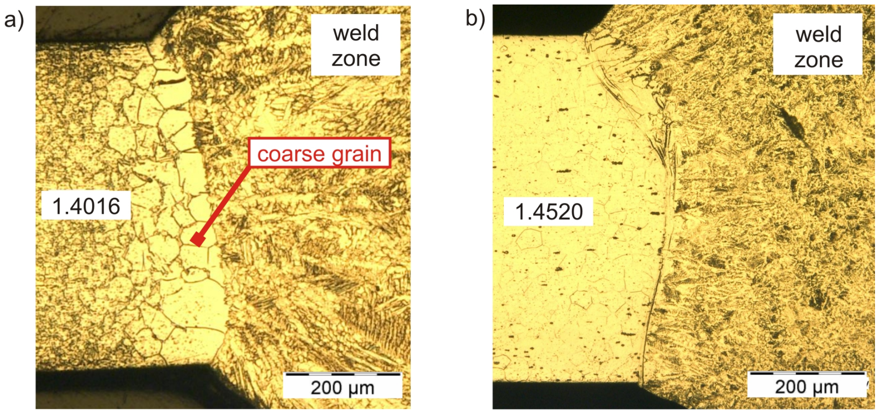

Fig. 7. Detailed view on the heat-affected-zones of connections with 1.4016 (a) and 1.4520 (b), welded with continuous-wave solid-state laser and filler wire 1.4576.

4 Characterization of the Welded Samples

As assumed, laser-welds without filler material feature a high turbulence of the element intermixture in the weld zone. This can be ascertained by element mappings, which highlight element dispersions within weld in false-colour illustration. For example, Figure 8 shows the nickel intermixture in a laser weld of 1.4301 and 1.4520.

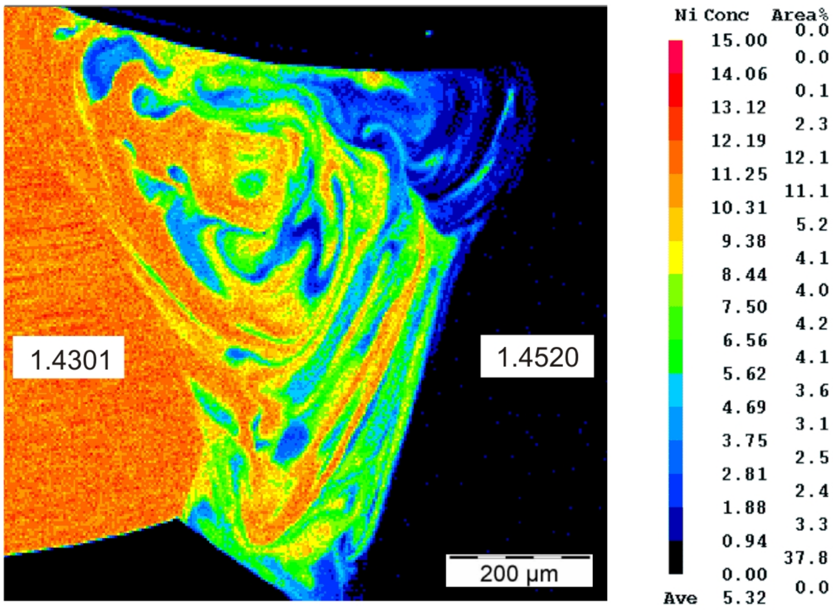

Fig. 8. Microprobe mapping for the element nickel in a laser-welded austenitic-ferritic connection: Left-hand side 1.4301, right-hand side 1.4016.

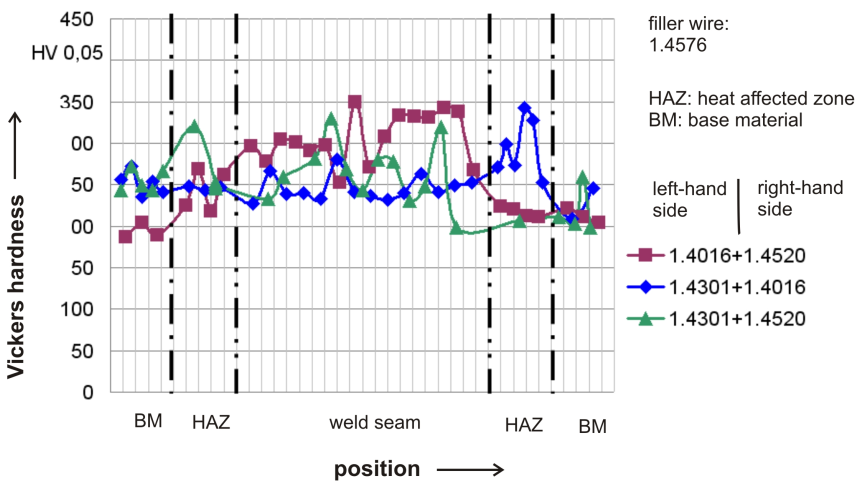

Fig. 9. Vickers hardness measurements of laser-welded austenitic-ferritic connections, welded with filler wire 1.4576**.**

According to Figure 8, the intermixture of alloying elements and particularly of nickel is obviously irregular and leads to a variance of chemical and mechanical characteristics within the weld. In contrast to that, welds with filler wire 1.4576 result in a quite harmonic element distribution. Measuring the hardness of welds with fillers, see Figure 9, it can be seen, that a more uniform element dispersion reduced the hardness fluctuation over the weld zone and limits the hardness traverse to an acceptable band width around the base metal state.

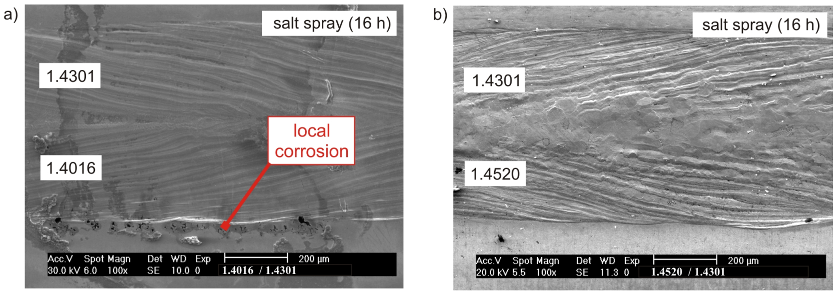

Fig. 10. SEM surface analysis of welds 1.4016 / 1.4301 (a) and 1.4520 / 1.4301 (b) with filler material 1.4576 after 16 hours of salt spray testing.

With regard of the chemical characterization of the welded sample salt spray tests with durations of 16 hours are performed. After the chemicals loading SEM analysis are used to examine the surfaces of the welds. As it can be seen in Figure10a) austenitic-ferritic welds with non-stabilized materials, such as 1.4016, feature local corrosion on top of the heat-affected-zone. This is exactly the area, where an excessive formation of coarse grain could be detected according to Figure 7a). At a closer look to Figure 10b) no corrosion can be found at welds with Ti-stabilized stainless steels after the same duration of salt spray testing. Therefore a Ti-stabilization has also to be recommended for chemical aspects and leads to austenitic-ferritic connections with an adequate corrosion resistance. By this way a sustainable replacement of nickel-alloy stainless steels by stabilized nickel-free materials can be realized without decreasing the chemical performance of laser-weld and therewith the whole assembly.

5 Conclusions and Outlook

The present article demonstrates the possibility to realized austenitic-ferritic stainless steel connections, by means of titanium-stabilized nickel-free ferritic materials. With appropriate welding process parameters and additional austenitic filler wires a regular intermixture in the molten state can be reached. By this way, adequate mechanical and also chemical characteristics of the laser welded connections are achievable, so that a nickel reduction does not effectuate a degradation of the corrosion resistance and the long-term stability of the relevant assembly. Summarized the present work will help introducing more nickel-free steels for as well stand of the art as future mobile systems with higher demands for chemical resistance. A limitation of nickel-alloys steels to mandatory installation points allows cost-effective and steady-price constructions in the automotive engineering and prevents welding and cutting operators from perpetual and excessive exposition by nickel oxides.

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