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Micro Electron Beam Welding of the hybrid material combination Nitinol and stainless steel without filler material

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Abstract. Nitinol, which consists of 50 at.-% nickel and 50 at.-% titanium, and stainless steels. These materials are widely used in medical engineering. Due to the versatile properties of Nitinol, for example shape memory and superelasticity, it finds application in implants and medical instruments. Because of its high-cost and poor machinability, there is a high demand for dissimilar welding of Nitinol components to stainless steel. During welding of titanium-containing alloys, like Nitinol, to ferrous metals like stainless steel, intermetallic phases between titanium and iron are formed. These phases are very brittle and lead to cracks and reduced mechanical properties of the joint. This publication intends to demonstrate the feasibility of producing weld seams with good quality by the use of Micro Electron Beam Welding. Due to a very accurate beam alignment and fast beam deflection, the composition and the level of dilution in the weld metal can be precisely controlled, resulting in a significantly reduced amount of intermetallic phases. Another aim of this paper is to show that the electron-optical monitoring can be used for quality assurance.

1. Introduction
The use of metallic materials in Medical Technology has become essential due to their excellent mechanical properties. Depending on the material, they possess very good corrosion resistance and biocompatibility and they will not be replaced by polymeric materials in the future. However, due to different requirements for example deformability, tensile strength or for cost reasons, it is necessary to combine different materials.

Nitinol is an intermetallic phase consisting of approximately 50 at.-% nickel and 50 at.-% titanium. Depending on its exact composition and heat treatment, it acts as a Shape Memory- or Superelastic Alloy. For medical purposes, superelastic alloys like SE508 are often used. Its benefit is an elastic deformation up to 8% at a level of approx. 400 MPa. [1, 2]

Figure 1 shows a stone-extraction basket as a typical example of a medical device made from Nitinol wires.

Basically, welding as a joining process is possible and also well-suited for medical devices. Depending on the materials to be welded, there are challenges with regard to the welding parameters to be selected as well as to the process control and their effects on the strength and corrosion
resistance. Especially dissimilar welding with titanium-containing materials has high demands on the accuracy and reproducibility of the welding process.

The aim of this paper is to show that Micro Electron Beam Welding meets these high requirements and that it enables producing sound welds between Nitinol and stainless steel without using a filler material.

![Figure 1. Stone-extraction basket as an example for the usage of Nitinol [3].](image)

2. Materials basics

2.1. Nitinol
Nitinol is an abbreviation for “Nickel Titanium Naval Ordnance Laboratory”. Shape memory effect was discovered at this laboratory in 1958. Nitinol can both be a Superelastic (SE) or Shape Memory Alloy (SMA). A diffusion-less transformation from austenitic to martensitic state (strain-induced superelasticity) or vice versa (thermally induced shape memory effect) takes place. There is just a little difference in the alloy composition of a few tenths of a percent between different alloys in a range from 49÷51 at.-% nickel. As a result of the difference in composition, transition temperatures changes significantly – from approximately -25 °C at superelastic alloys to +80 °C or even higher at SMA [1, 4].

| Table 1. Typical characteristics of different NiTi alloys [4, 5]. |
|---------------------------------------------------------------|
| NiTi (SE), austenitic | NiTi (SMA), martensitic |
| Nickel content | 50.8±0.4 at.-% | 49.7±0.4 at.-% |
| Titanium content | balance | balance |
| Young’s modulus | 70÷80 GPa | 23÷41 GPa |
| Tensile strength, annealed | ~ 900 MPa |
| Tensile strength, cold-work hardened | up to 1,900 MPa |
| Poisson’s ratio | 0.33 |
| Elongation at break, annealed | 20÷60% |
| Elongation at break, cold-work hardened | 5÷20% |
| Melting point | ~1310 °C |
| Density | 6.45÷6.5 g/cm³ |
| Thermal conductivity | ~18 W/mK | ~9 W/mK |
| Coefficient of thermal expansion 20÷800 °C | 10÷11•10⁻⁶ 1/K | ~6.7•10⁻⁶ 1/K |
Table 1 shows typical characteristics of Nitinol alloys, figure 2 a stress-strain diagram of the commercial available superelastic NiTi alloy SE508.

It is clearly visible that the superelastic effect depends strongly on temperature. Whereas the stress plateau is 550 MPa @ 30 °C with a maximum superelastic strain of 7%, the stress plateau decreases to 400 MPa @ 5 °C with a superelastic strain of max. 6%. At -30 °C, which is a bit lower than transition temperature, the SE effect will not be present.

![Stress-strain diagram of Nitinol alloy SE508 at different temperatures](image)

**Figure 2.** Stress-strain diagram of Nitinol alloy SE508 at different temperatures [6].

In addition to the mentioned effects, Nitinol has a very good corrosion resistance and biocompatibility due to its high titanium content. But this material also has some disadvantages: its very high price due to the high purity and exact alloy composition needed and the high-cost and poor machinability by conventional milling or similar processes. [7, 8]

For this reason, there is a high industrial demand for dissimilar welding of Nitinol to different metals and alloys. For the welding experiments described in the following chapters, Nitinol alloy SE508 was used.

2.2. **Stainless steels**

Stainless steels are steels with at least 12–13% chromium. Due to the high chromium content, a thin passive layer protects the surface from corrosion. Often nickel is added to obtain an austenitic structure, which has better mechanical properties than a ferritic or martensitic structure. Small amounts of elements like titanium or niobium can increase the corrosion resistance.

Austenitic steels are widely used for medical devices. The main reasons are the good machinability, the low price as well as sufficient corrosion resistance and biocompatibility. Table 2 shows the properties of two stainless steels which are widely used for medical devices and instruments, whereas 1.4310 steel is mostly used for wires and springs and 1.4404 for machined parts [5].
Table 2. Typical characteristics of different stainless steels for medical purposes [9, 10].

| Steel Type | Young’s modulus | Tensile strength, annealed | Tensile strength, cold-work hardened | Poisson’s ratio | Elongation at break, annealed | Elongation at break, cold-work hardened | Melting point | Density | Thermal conductivity | Coefficient of thermal expansion |
|------------|-----------------|---------------------------|------------------------------------|----------------|-------------------------------|---------------------------------------|---------------|---------|-------------------|-------------------------------|
| 1.4310 X10CrNi18-8, AISI 301 | 200 GPa | ~800 MPa | up to 2100 MPa | 0.29 | ~40% | 1÷15% | ~1420 °C | 7.9 g/cm³ | 15 W/mK | 18•10⁻⁶ 1/K |
| 1.4404 X2CrNiMo17-12-2, AISI 316L | 200 GPa | 500÷700 MPa | up to 1250 MPa | 0.28 | ~40% | 5÷15% | ~1400 °C | 8 g/cm³ | 15 W/mK | 14.7•10⁻⁶ 1/K |

3. State of the art of beam welding Nitinol to stainless steel

There are some challenges in fusion welding of the hybrid material combination Nitinol and stainless steel. Figure 3 shows an isothermal section from the ternary phase diagram of the complex Fe-Ni-Ti system at 900 °C. There are no ternary intermetallic phases in this system, but most of the binary phases provide a good solubility for the third element. More information about the phase system can be found in [1] and [11].

Because intermetallic phases, which are rich in Fe (Fe₂Ti) and Ti (NiTi₂), are very brittle and lead to cracking, they have to be avoided in the weld material. Solidification cracking can be reduced by producing a weld metal with >40% Ni or Fe and <45% Ti, which can be achieved by a precise beam alignment on one of the joining parts [12].
In 2010, H. Gugel used a pulsed Nd:YAG Laser for butt welding of Nitinol and stainless steel sheets with a thickness of 1 mm without any filler material. A beam displacement of 0.3 mm to the NiTi sheet created weld seams free of cracks and nearly no other defects, which is shown as a cross section in figure 4. The ultimate tensile strength of this weld seam was 310 MPa, so that the specimen did not reach the superelastic plateau stress level of approx. 400 MPa [1].

R. Stark and N. Süleymanov also used a pulsed Nd:YAG Laser for butt welding of Nitinol to stainless steel sheets. In opposite to H. Gugel, they used nickel and tantalum wires and foils as a filler material to reduce the amount of brittle intermetallic phases in the weld material. With nickel filler material, it is possible to generate virtually crack and defect free weld seams as shown in figure 5. Due to the higher energy input needed to melt the filler material, the width of the weld seam is much larger than in the ones made by H. Gugel. The ultimate tensile strengths of all specimens is measured less than 300 MPa, so that the superelastic plateau stress level of the Nitinol could not be reached [13].

**Figure 4.** Cross section of a pulsed Nd:YAG Laser weld seam between a Nitinol and stainless steel sheet [1].

**Figure 5.** Cross section of a pulsed Nd:YAG Laser weld seam between stainless steel and Nitinol sheets. Nickel wire is used as filler material [13].

### 4. Welding setup and parameters

For their own investigations, the Micro Electron Beam Welder SEM108, manufactured by pro-beam AG&Co. KgAA (Planegg, Germany) and JSC Selmi (Sumy, Ukraine) at the Department for Cutting and Joining Manufacturing Technologies is used. Key specifications of the machine are shown in table 3. Metal sheets with a size of 12.5×25 mm and a thickness of 0.3 mm, made from Nitinol SE508 and stainless steel 1.4310 in slightly work-hardened condition (~1150 MPa tensile strength), are used as welding specimens. Both sheets are clamped in a special fixture, so that they are positioned accurately with virtually no gap for butt welding. A groove at the joining position ensures a free forming of the seam root. Figure 6 depicts a photo of the fixture.

**Figure 6.** Welding fixture.
Table 4 gives an overview of the used welding parameters. Both parameter sets are chosen in a way that full penetration welds are achieved. Parameter set “1” with a lower welding speed and lower beam power will result in conductive-mode welding, parameter set “2” with a higher beam power will result in keyhole-mode welding. In previous experiments, a beam offset of 0.15 mm in the direction of stainless steel gave the best results with regards to cracking. Weld seams without an offset or an offset in the direction of Nitinol are more liable to cracking. Samples welded with these parameters always showed a longitudinal crack propagation in the weld seam, in case of a beam offset to Nitinol, the specimens even show a failure of the welding in the fixture.

Table 3. Specifications of SEM108 Micro EB Welder.

| Specification                     | Value                              |
|-----------------------------------|------------------------------------|
| Micro Electron Beam Welding Machine SEM108 |                                    |
| Acceleration voltage              | 10÷60 kV                           |
| Beam Current                      | 0.01÷20 mA                         |
| Beam diameter @ 1 mA              | ~30 µm                             |
| Vacuum                            | up to 10⁻⁶ mbar, oil-free pump system |
| Working chamber size              | cubic, 30 l, equipped with 5-axis manipulator |
| Deflection control system         | pro-beam MiniMod, 5 MHz deflection frequency |
| Electron-optical monitoring resolution | 5 µm @ 5 MPx/s                     |

Table 4. Parameter sets used for welding.

| Parameter set “1” | Parameter set “2” |
|-------------------|-------------------|
| Accel. Voltage    | 60 kV             | 60 kV             |
| Beam current      | 1.25 mA           | 2.5 mA            |
| Focus             | Surface           | Surface           |
| Welding speed     | 15 mm/s           | 50 mm/s           |
| Offset            | 0.15 mm (steel)   | 0.15 mm (steel)   |

5. Results

With both parameter sets, it is possible to generate a joint between Nitinol and stainless steel. Cross sections (etched with V2A etchant) of the weld seams are shown in figure 7. Cross section “1” shows a thorough mixing of the elements, whereas “2” (welded with a higher feed rate) shows areas of unmixed materials. The different interaction time between the beam and the samples is the main reason. At lower welding speeds, there is more time for convective mixing of the molten materials, whereby differences in density and surface tension are the reason for the material flow [14]. The longer interaction time of the beam is also the reason for the higher width of weld seam “1” compared to weld seam “2” due to heat conduction.

Both the welded samples contain intermetallic phases, whereas the total content is higher in sample “1”. Due to this intermetallic phases, which are mostly from the type Fe₂Ti, the hardness of the weld material is much higher than that of the base materials. Hardness in welding zone can be up to 920 HV0.1. Nitinol base material shows values of approx. 270 HV0.1 and stainless steel base material values of approx. 420 HV0.1. In general, hardness values in sample “1” are slightly higher and distributed more uniformly than in sample “2”.

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The joints welded with a feed rate of 15 mm/s show some crater cracks, which is depicted in the electron-optical picture of the weld seam in figure 8. Also a small crack parallel to the surface in the upper part is visible in the cross-section. On the contrary, seams welded with parameter set “2” do not show any surface inhomogeneity or cracks in the cross-section, figure 9. Other defects like pores or weld spatter cannot be found on the surface or the cross-sections.

A stress-strain diagram for both samples and also the base materials is shown in figure 10. In quasistatic tensile tests, the measured ultimate tensile strength of sample “1” is 202 MPa, so that the superelastic plateau of Nitinol is not reached. It can be seen that the superelastic plateau is nearly reached by sample “2”. The ultimate tensile strength of the sample is 434 MPa. Both samples showed a brittle fracture. Sample “1” broke in the middle of the weld seam, sample “2” at the Nitinol-sided fusion line. Measurements were done at room temperature (22 °C).

The reasons for the failure of the weld seam are the high hardness and brittleness of the weld metal. Due to a big difference in Young’s modules, different Poisson’s ratios and the strain-induced martensitic transformation, the stress level is the highest directly at the interface between Nitinol and the weld material.
6. Conclusion
The experiments have shown that it is possible to join Nitinol to stainless steel sheets in butt welding position with higher tensile strength than Laser welding in full penetration mode (even with filler material). [1, 13, 15]. Depending on the parameters, welds can be free of cracks and other defects. Anyway, the specimen failed in the weld material at quasistatic tensile testing due to a high hardness and brittleness of the weld metal.

The welding parameters, like beam power and feed rate, influence the tensile strength even more than beam deflection or figures. In this experiments it was shown that a parameter set with a higher welding speed and lower heat input gave better results than the one with lower welding speed and higher heat input. It was also shown that the electron-optical depiction is an appropriate tool to check the joint for cracks after welding.

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