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# Influence on the weld strength of high-strength fine-grained structural steels by thin-film-coated GMA welding electrodes

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# Influence on the weld strength of high-strength fine-grained structural steels by thin-film-coated GMA welding electrodes

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**Abstract.** The increasing demand for high-strength fine-grain steels for the purpose of reducing the weight of steel structures and increasing payloads, is driving forward the development of fine-grain steels. However, with the currently available welding consumables, it is not possible to achieve the strengths of modern fine-grain steels with a grade of S1300QL in the weld metal. As a result, there is a need for novel welding consumables, which guarantee high-strength joints. The application of thin, functional layers on GMA welding electrodes by a PVD coating process makes it possible to influence the mechanical-technological properties to an extent which cannot be achieved by state-of-the-art technology. The sputtering of different elements on the substrate material of GMA electrodes and the layer thickness has an influence on the welding process and the welding metal. Especially, the influence on the microstructure by a niobium coating of different layer thickness is presented. Furthermore, the changes in the mechanical properties of the weld metal depending on the layer thickness or rather the niobium content are shown. In particular, the fine-grain and carbide-forming effect of niobium and the influence on the mechanical properties are presented. Here niobium contents between 0.5 wt.-% and 1.5 wt.-% are in the focus of investigations.

## 1. Introduction

Due to their high strength and toughness, fine-grain steels are used, among others, in the field of steel structures and in mobile crane construction with the aim of reducing the weight and increasing payloads,[1]. Considering the requirements in these applications, the development of fine grain steels is progressing towards increasing yield strengths while maintaining good toughness properties through the addition of alloying elements such as chromium, nickel or molybdenum and corresponding tempering treatments **Figure 1**, [2].
Steels with a carbon content of ≤ 0.2% and small amounts of alloying elements have a low tendency to harden and are therefore easily weldable without a particularly high risk of cracking, [3].

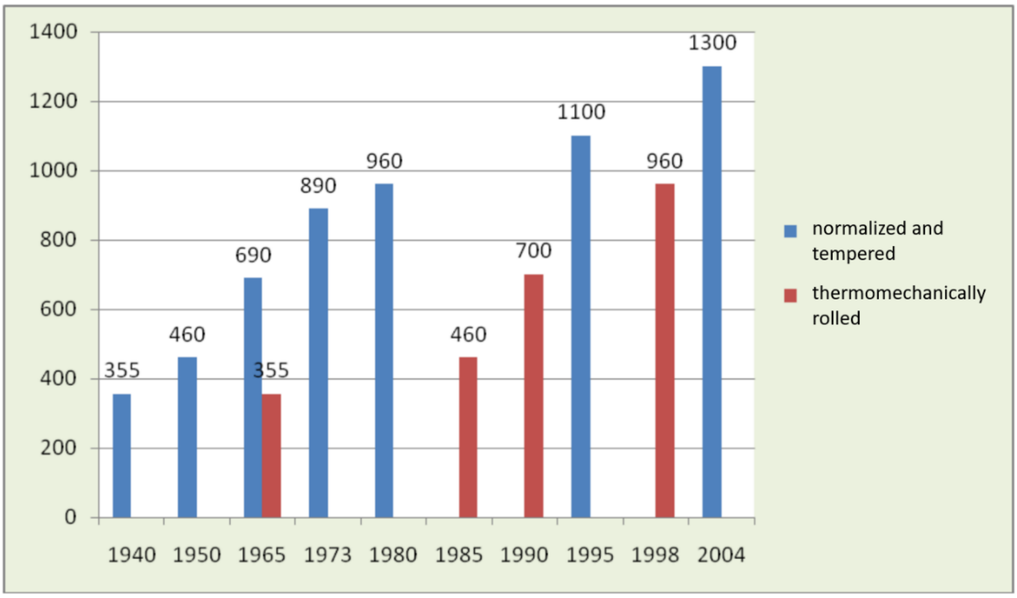


**Figure 1:** Development of the yield strength of fine grain steels based on [2]

During welding processing, a drop in strength occurs in the area of the weld. This can be influenced by the filler material and its alloy. Due to the deformability required in the wire drawing process, the design of the alloy composition of the welding wire and thus also the influence on the weld metal is limited.
The idea of using the physical vapor deposition to coat GMA welding wire electrodes enables the application of functional layers on the surface after the wire drawing process, thereby expanding the possibilities of designing the alloy composition in the weld metal. The influence of low niobium contents in the heat affected zone of welds in fine grain steels was investigated simulatively by [4] whereby a grain refining effect was detected and a positive influence on the yield strength and the tensile strength was determined. The use of niobium as a micro-alloying element in a proportion of less than 0.1% by weight in the production of modern fine-grained steels was also investigated by Hulka, Kern and Schriever. In addition to the wear resistance, the influence of niobium on the toughness properties of welded joints is considered and a positive effect on the notched impact strength is determined, as well as a shift of the transition temperature T27 towards lower temperatures, [5].
With the aid of the coating process described here, alloying elements in previously unachieved mass percentages can be introduced into the weld metal via the filler material and thus examined with regard to the effects on microstructure and mechanical-technological properties. The aim is the development of a welding consumable for the welding processing of modern, high-strength fine-grained steels with yield strengths in the range of 1300 MPa, whereby the strength in the base material is to be achieved or even exceeded to allow an overmatching. Currently, there are no welding consumables that guarantee these strengths in the weld metal, [6].
Initial investigations with coated welding wire electrodes show that they are suitable for increasing the strength in the weld metal. The tensile strength and yield strength of the weld metal can be influenced by the targeted integration of alloying elements over thin-film coated welding wire electrodes.

## 2. Process of welding wire electrode coating

The substrate material used is a Mn4Ni2CrMo alloy GMA welding wire electrode with a diameter of 1.2 mm. Magnetron sputtering in a PVD system is used to apply niobium thin-film layers to the substrate material, **Figure 2**. The procedure has already been described in detail in [7]. An inert gas is decomposed in ions and electrons by applying a high voltage in the evacuated process chamber. Positively charged ions are accelerated and, when hitting the cathode (target), eject atoms and molecules from the coating material by impulse transfer. In the case of the magnetron sputtering used here, permanent magnets are additionally arranged behind the targets. The superposition of magnetic and

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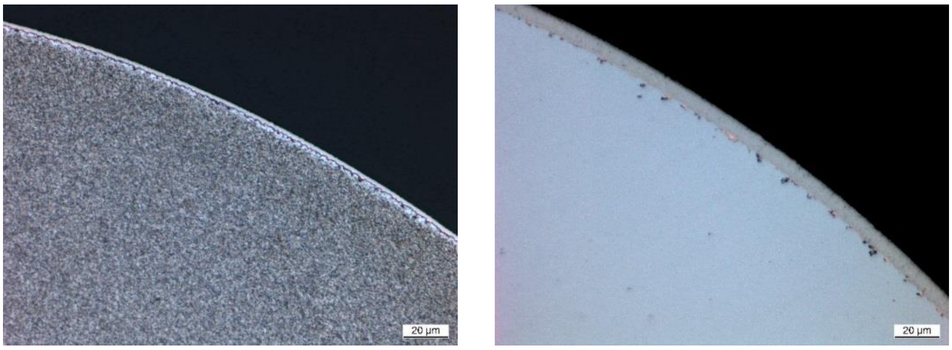
electric fields directs the electrons to a helical path and increases the ionization probability. This additionally increases the deposition rate, [8].


**Figure 2**: PVD coating system [7]

**Figure 3:** Device for holding the welding wire in the system [7]

In the experiments shown here, the welding wire is fed to the machine and coated batchwise. For this purpose, it is wound onto a device in the coating chamber, **Figure 3**. Among other parameters, in this process, the layer thickness correlates with the process time and can thus be influenced in a targeted manner. The micrographs of the welding wire electrodes in **Figure 4** show thin-film layers of niobium with a layer thickness of 3 µm and 6 µm.




a.) niobium coating 3µm b.) niobium coating 6µm

**Figure 4:** Micrographs of GMA welding wire electrodes with niobium coatings in different layer thicknesses

### 3. Material and metallography

To carry out the welding tests, the high-strength fine-grain structural steel S960QL is used as the base material. The chemical composition of this steel is defined according to DIN EN 10025-6, as shown in **Table 1**. In direct comparison, the composition of the filler metal Mn4Ni2CrMo according to DIN EN ISO 16834 is listed. In order to be able to detect the transition of the elements from the welding consumable into the weld metal, single-layer surface welds were performed, from which samples were taken for spectrographic investigations. The results are also summarized in **Table 1**.

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**Table 1: Chemical composition of the base material, the steel and the corresponding weld metal depending on the filler material**

| | % max. DIN EN 10025-6 | welding wire Mn4Ni2CrMo DIN EN ISO 16834 | weld metal Mn4Ni2CrMo | weld metal Mn4Ni2CrMo + 6µm Niob |
|---|---|---|---|---|
| **C** | 0,20 | 0,12 | 0,1184 | 0,0979 |
| **Si** | 0,80 | 0,60 - 0,90 | 0,4540 | 0,4555 |
| **Mn** | 1,70 | 1,60 - 2,10 | 1,190 | 1,193 |
| **P** | 0,020 | 0,015 | 0,0066 | 0,0045 |
| **Cr** | 1,5 | 0,20 - 0,45 | 0,4434 | 0,4013 |
| **Mo** | 0,70 | 0,45 - 0,70 | 0,4267 | 0,4292 |
| **Nb** | 0,06 | - | 0,0092 | 1,022 |
| **Ni** | 2,0 | 1,8 - 2,3 | 1,619 | 1,752 |
| **Ti** | 0,05 | - | 0,0130 | 0,0078 |

In the first investigations with the filler material of the alloy Mn4Ni2CrMo and a 6µm thick niobium coating (Mn4Ni2CrMo + 6 µm niobium), the transition of the niobium into the weld metal can be detected by optical emission spectroscopy.
The spectroscopic analysis shows that the carbon content in the investigated compounds is about 0.1% and about 1% niobium are included. Up to about 0.15% C, the formation of Fe3Nb2 is observed, [9]. According to the ternary system iron-niobium-carbon the formation of α-ferrite, niobium carbides (Nb4C3) and Laves phases (Fe3Nb2) is to be expected, **Figure 6**. To assess the microstructure an image recording in the cover layer of the weld and one in the layer below (hereafter referred to as "middle-layer") was made, **Figure 5**.

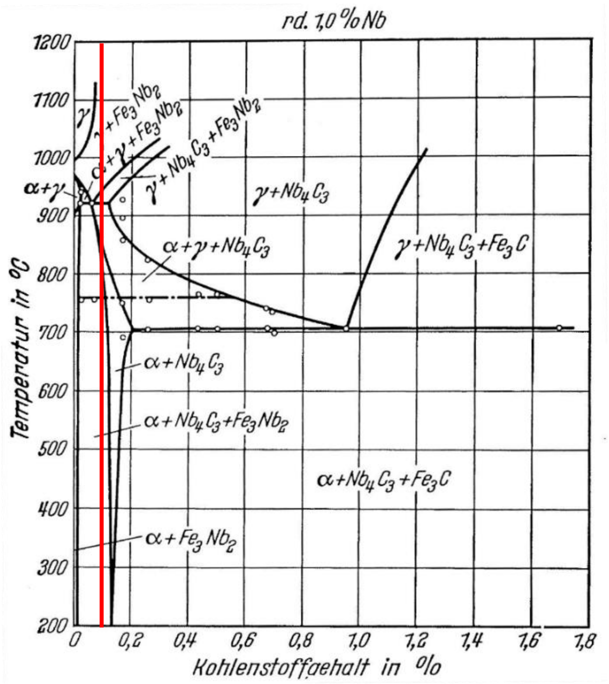


**Figure 5:** Section through the ternary system iron-niobium-carbon parallel to the iron-carbon side [9]

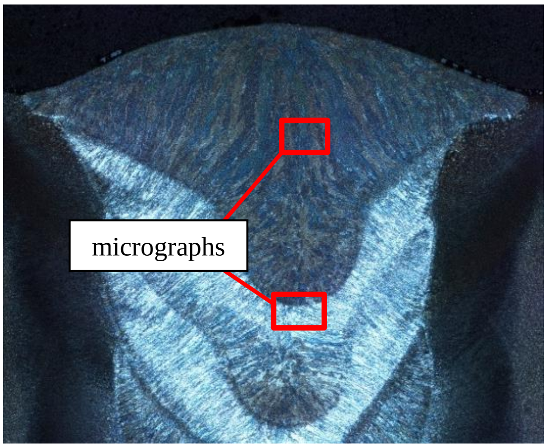


**Figure 6:** Position of micrographs in the welding seam

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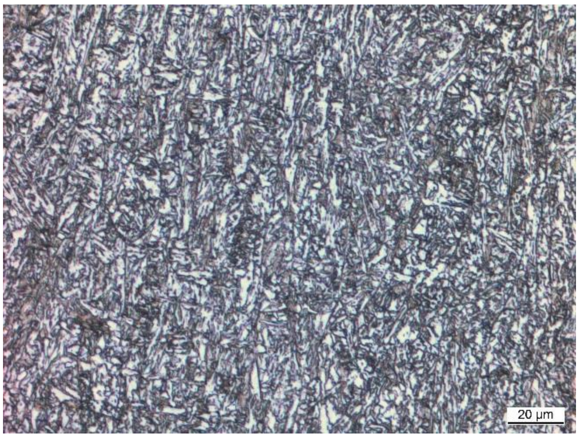
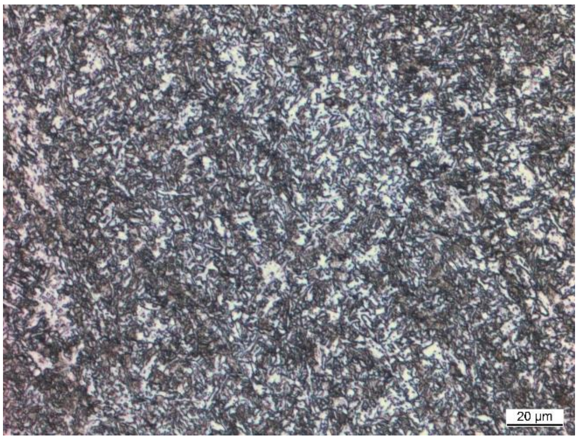
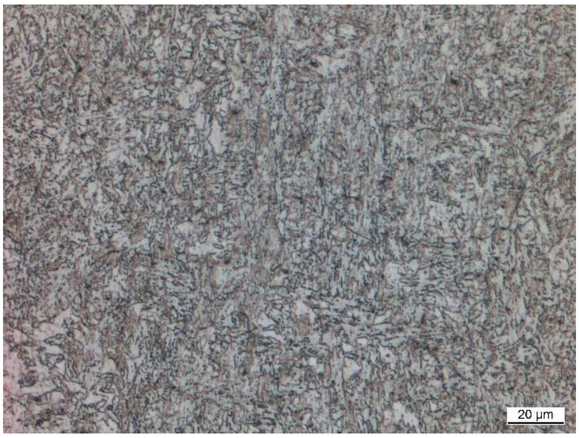
The influence of the increased niobium content on the microstructure becomes clear from the micrographs in Figure 7a.) bis f.). In each case, micrographs of the top layer (left) and the middle layer (right) are shown.



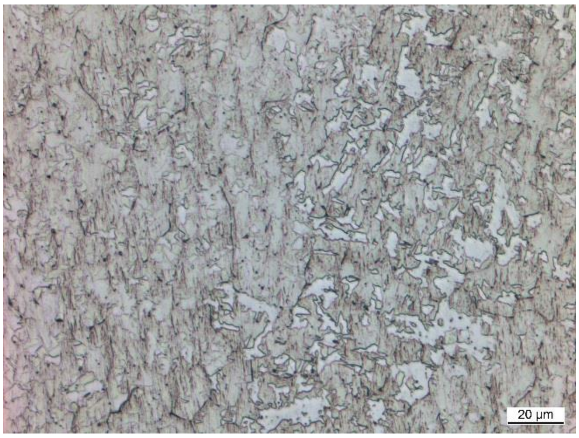

a) Mn4Ni2CrMo top layer




b) Mn4Ni2CrMo middle layer

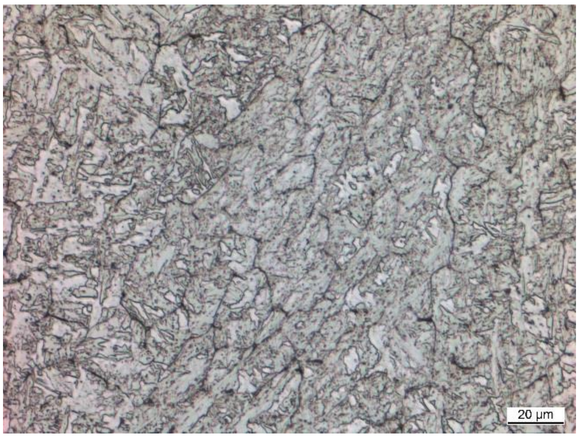



c) Mn4Ni2CrMo + 3µm niobium top layer




d) Mn4Ni2CrMo + 3µm niobium middle layer


e) Mn4Ni2CrMo + 6µm niobium top layer




f) Mn4Ni2CrMo + 6µm niobium middle layer

**Figure 7:** Welded products of the filler material Mn4Ni2CrMo without coating and with different thicknesses of niobium coating

In all cases, microstructural changes between the cover layer and the middle layer of the welded joint can be recognized, which are due to diffusion and recrystallization processes by the reheating.

**Figure** 7**a** und **Figure 7b** show the structure of the uncoated filler material Mn4Ni2CrMo. This mainly produces ferritic-bainitic microstructure. Micro-alloying elements allow the fine-grained structure to be retained in the center of the weld by precipitates that block grain growth and reduce the re-crystallization rate of austenite, [10].
In direct comparison, a much finer grain structure is found in the cover layer of the weld metal, which is produced with Mn4Ni2CrMo + 3 µm niobium. On closer examination, the position of niobium carbides (Nb4C3) and Laves phases (Fe3Nb2) can be assumed. In the middle layer, the fine-grained structure dissolves due to the repeated temperature influence of the cover layer and diffusion processes occur at the grain boundaries, Figure 7c und Figure 7d.
The microstructure, which is produced with Mn4Ni2CrMo + 6 µm niobium, appears coarser in the micrograph, Figure 7e und Figure 7f. The brittle-hard phases (carbide and Laves phases) are more pronounced in the cover layer. The micrograph of the middle layer allows the hypothesis that the diffusion processes are therefore more distinct here and therefore the primary austenite grain boundaries are clearly recognizable after the production of the cover layer.

## 4. Determination of mechanical technological properties

The influence of the microstructures on the mechanical technological properties of the welded joints was investigated by notched bar impact tests according to DIN EN ISO 148-1 and tensile tests according to DIN EN ISO 6892-1,[11] [12].
The focus of the investigations is the mechanical strength of the weld metal, which is why the samples for the analysis of the microstructure as well as for the investigation of the mechanical technological properties are taken according to DIN EN ISO 15792-1,[13]. The location of the samples in the weld metal is shown in **Figure 8** and **Figure 9**.

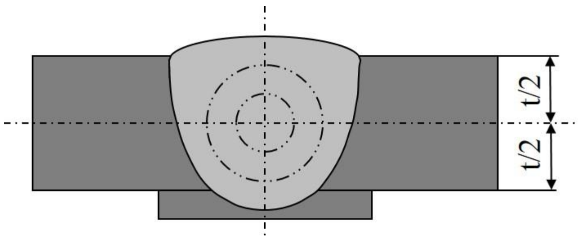



**Figure 8:** Location of the tensile specimens in the weld metal

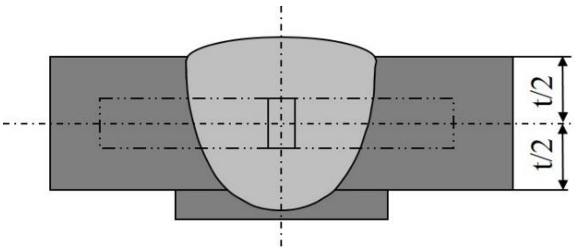



**Figure 9:** Location of notched bar impact tests in weld metal

For initial investigations, compounds with Mn4Ni2CrMo, Mn4Ni2CrMo + 3 µm niobium and with Mn4Ni2CrMo + 6 µm niobium are welded before impact test samples and tensile specimens are taken. The welding parameters are given in **Table 2**.

**Table 2:** welding parameters

| parameter | value |
|---|---|
| wire feed | 9,3 m/min |
| voltage | 30 V |
| current | 290 A |
| welding speed | 300 mm/min |
| energy per section | 1,74 kJ/mm |

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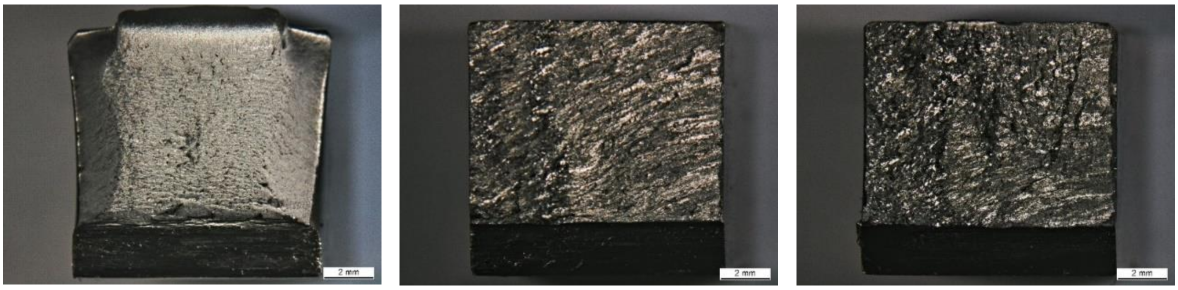
In the notched-bar impact tests, the notched-bar impact work falls considerably due to the niobium introduced into the weld metal via the filler metal. **Table 3** compares the average notched impact values of three impact tests each.

**Table 3**: Impact work as a function of the niobium coating

| Filler metal | Impact work as a function of the niobium coating in J |
|---|---|
| Mn4Ni2CrMo | 107,5 |
| Mn4Ni2CrMo + 3µm niobium | 6,67 |
| Mn4Ni2CrMo + 6µm niobium | 5,17 |

The brittle material failure can be traced back to the brittle-hard, intermetallic Laves phases which are not plastically deformable at room temperature and the niobium carbides. An embrittlement of the material was therefore to be expected. The fracture surfaces of the impact test samples are shown in **Figure 10**.



a.) Mn4Ni2CrMo b.) Mn4Ni2CrMo + 3 µm Niob c.) Mn4Ni2CrMo + 6 µm Niob

**Figure 10:** Fracture surfaces of impact test samples with different niobium content

**Figure 10a** shows the fracture surface of an impact test sample from the weld metal, which was welded by the uncoated filler material Mn4Ni2CrMo. The comparatively ductile behavior of the sample is reflected in the illustrated deformation fracture.

**Figure 10b** and **Figure 10c** show the fracture surfaces of the samples using the niobium-coated welding wire. Both samples show macroscopically no plastic deformation at the fracture surface and show brittle material failure. The sample with a lower niobium content indicates a more oriented fracture surface structure, which is significantly less pronounced in the sample with a higher niobium content.

The influence of the niobium contents on the strength of the weld metal becomes clear in the tensile test and the corresponding stress-strain diagrams.

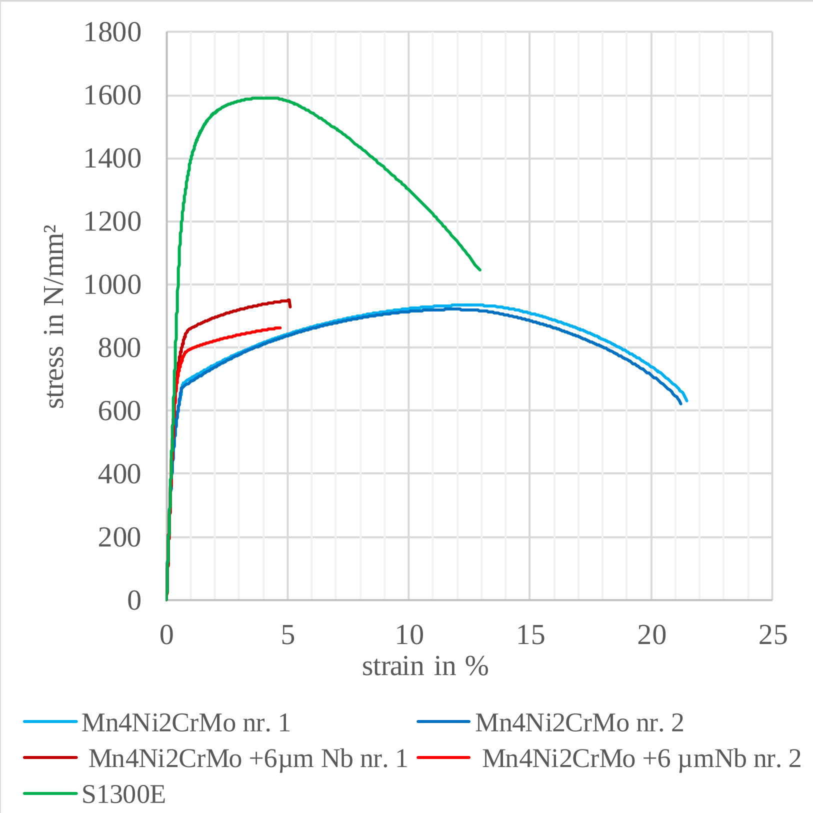



**Figure 11:** Stress-strain diagram for filler metals Mn4Ni2CrMo and Mn4Ni2CrMo + 6 µm niobium

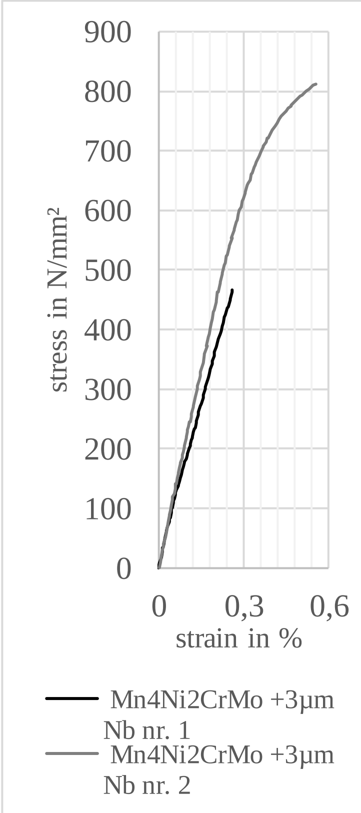



**Figure 12:** Stress-strain diagram for Mn4Ni2CrMo + 3 µm niobium

With a layer thickness of 3 µm niobium on the welding wire, the weld metal has such a brittle behavior that neither data for the yield strength of Rp0.2 nor for the tensile strength can be determined, **Figure 12**. With a further increase in the niobium content (layer thickness 6 µm), the elongation at break is lower in comparison to the uncoated filler metal and the behavior of the material is also more brittle, **Figure 11**. In addition, the stress-strain behavior of the modern fine grain structural steel S1300E was determined. The comparison shows that the yield strength can be positively influenced by the coated filler metals, but further research work is necessary in view of such high strengths. The averaged values are summarized in **Table 4**

**Table 4:** Average characteristics of the tensile test according to DIN EN ISO 6892-1

| | $Rp_{0,2}$ in MPa | tensile strenght in MPa | elongation at break in % |
|---|---|---|---|
| Mn4Ni2CrMo | 605,3 | 927,9 | 21 |
| Mn4Ni2CrMo + 3µm niobium | not evaluated | not evaluated | 0,1 |
| Mn4Ni2CrMo + 6µm niobium | 765 | 873,5 | 4,5 |

The yield strength of the weld metal can be increased by about 26% by the addition of 1 wt .-% niobium. With increasing niobium content, the elongation at break decreases first and then increases again to 4.5%. By comparison, the base material S960QL used according to DIN EN 10025-6 has an elongation at break of at least 10%, [14]

**Figure 13** shows the determined values for the elongation at break and an indicated possible course over the layer thickness of the niobium. For a comparison with the base material, the elongation at break of the S960QL is also shown.

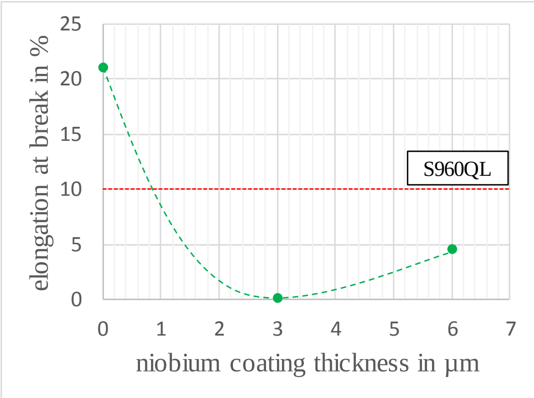



**Figure 13**: elongation at break depending on the niobium coating thickness

Further investigations with a higher niobium content are intended to show whether the illustrated relationship is a local minimum of the elongation at break and to what extent the elongation at break can be raised again with increasing niobium content in order to reach the level of the base material with simultaneously increased yield strength.

## 5. Summary and research needs

In view of the demand for welding consumables for modern fine-grain structural steels, the presented method opens up new opportunities for research. The investigations show that it is possible to develop welding consumables with multifunctional thin-film layers, which not only have a direct influence on the weld metal and its strength, but also on the arc and the processability of the filler material. This allows the investigation of alloying elements in previously unachieved proportions of the weld metal.
The yield strength of the weld metal can be increased by 26% through the filler metal Mn4Ni2CrMo, on which a 6 µm thick layer of niobium was applied. However, the toughness of the weld metal decreases significantly. On the basis of the knowledge acquired, investigations of further niobium content as well as other alloying elements are planned. whereby the influence of the thin film coatings on the mechanical technological characteristics of the weld metal should be considered.
The goal is to achieve or even exceed the strengths of modern fine grain steels (overmatching). The challenge is the combination of increased strength with sufficient toughness properties, which should result directly from the weld structure without any possibilities for aftertreatment.

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