Welding in the World
https://doi.org/10.1007/s40194-021-01086-3

RESEARCH PAPER

Development of surface coatings for high-strength low alloy steel filler wires and their effect on the weld metal microstructure and properties

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Received: 17 September 2020 / Accepted: 28 January 2021
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Abstract
The lightweight construction of steel structures is often limited by the mechanical properties of the weld metal. The strength values of modern base materials are not achieved in the weld metal. There is a considerable need to develop welding consumables that allow the processing of modern fine-grained structural steels without limiting their potential. The Physical Vapor Deposition (PVD) coating of welding wire electrodes can increase the strength of the weld metal of a Mn4Ni2CrMo welding wire electrode by up to 30%. By using different coating elements, the Hall–Petch relationship can be exploited and such an increase in strength can be achieved. Especially by applying titanium, vanadium, and yttrium coatings, the strength of the weld metal can be increased. Due to a multilayer structure of the coating, the weld metal and the process can be influenced independently of each other. The effects of mono-element coatings and multi-component coatings on the weld metal and the process are discussed. PVD coatings allow welding wire electrodes to be individually adapted to the requirements.

Keywords High-strength steel · GMA welding · Microstructure · Mechanical properties · Titan · Yttrium · Vanadium

1 Introduction

The constantly increasing demands by architecture and industrial plant engineering are met by lightweight constructions. Steel development in this field of research is being driven forward, particularly with the aim of reducing dead weights and increasing load-bearing capacities. Modern fine-grain structural steels achieve yield strengths of 1300 MPa, thus enabling reduced material usage [1, 2].

Recommended for publication by Commission IX - Behaviour of Metals Subjected to Welding

The original online version of this article was revised due to a retrospective Open Access order.

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The strength increase of high-strength steels is primarily achieved by grain refinement and is based on the Hall–Petch relationship. The influence of different alloying elements on the weld metal, grain size, and crystallization is therefore of high interest in research on high-strength steels. Niobium has proven to be an element particularly suitable for grain refinement [3, 4]. In addition to niobium, other elements such as titanium are also suitable for influencing the weld metal [5, 6].

The limiting factor when using these steels is the strength that can be achieved in the weld metal. The strength of the base materials cannot be achieved in the weld metal with the currently available filler metals, so that the development of suitable welding wire electrodes is necessary.

Physical Vapor Deposition (PVD) coating processes enable thin layers to be applied to welding wire electrodes [7, 8]. The resulting wire electrodes can be used to process the steel grades described [9]. Wire electrodes of the quality Mn4Ni2CrMo can be used as substrate [10]. By varying the applied layer thickness of different elements, the mechanical properties of the weld metal can be investigated with respect to different mass fractions of the layer elements. In addition to mono-element coatings, the properties of the weld metal can be influenced by an adapted composition of several coating elements (multi-component and multilayer coatings).

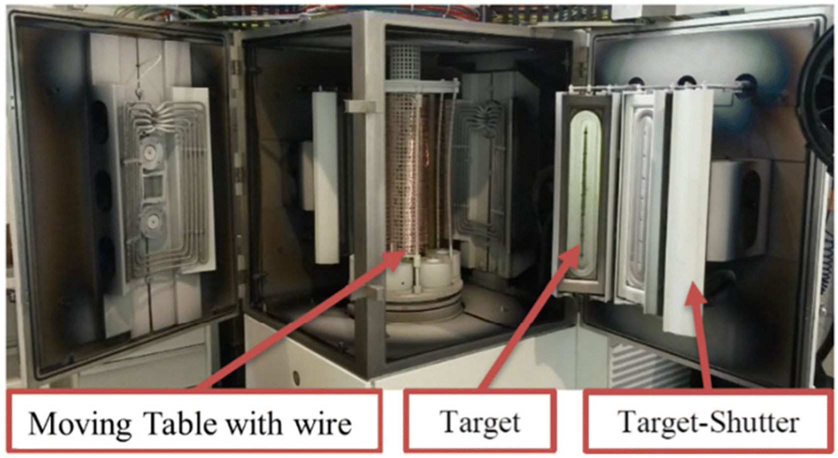

Fig. 1 PVD coating system [9]

The state of the art is to adapt the alloying of welding wire electrodes in order to achieve higher strengths in the weld metal. This is possible in that the wire drawing process itself is still possible despite the limited ductility. A further approach to a far-reaching influence on the weld metal strength is the use of flux-cored wire electrodes, although the hydrogen content is increased compared to a solid wire electrode [11].

The coated wire electrode approach extends the range over which the weld metal composition can be influenced without the limitations of the wire drawing process or the hydrogen problems of flux-cored electrodes.

The process of wire coating is done with the coating system shown in Fig. 1.

The figure shows the coating chamber of the Cemecon CC-800/9 Custom coating system, which is used to apply PVD coatings according to industrial standards. A material is vaporized in a vacuum chamber and condenses in thin layers on the substrate material (welding wire). Therefore, the process gas (argon) is ionized by an applied voltage. The argon ions are accelerated in the direction of the coating material (target) and vaporize it. The vaporized material is guided through an electrical field and hits the parts to be coated.

The substrate material used in the described investigations is a GMAW wire electrode of the alloy Mn4Ni2CrMo with a diameter of 1.2 mm. The wire electrode is fed into the system in batches and coated. For this purpose, it is wound onto a carrier structure in the chamber. To determine the respective total coating thickness, an additional sample was coated in each process. The coating thickness was determined on the basis of calotte grinding. In the case of multilayer coatings, the total coating thickness was determined.

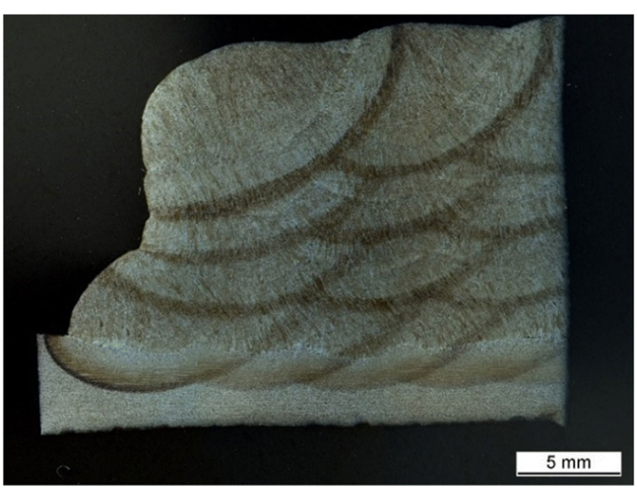

Fig. 2 Microsection of a bead on plate weld

2 Sample preparation and examination

2.1 Experimental procedure and sampling

The welding wire electrodes were welded on a substrate plate to determine the mechanical properties of the wire electrodes. Several welds side by side and several layers on top of each other (bead on plate weld) are shown in the micrograph in Fig. 2. The applied weld metal had a length of 200 mm and a width of 60 mm and was applied about 15 mm high. The substrate plate was preheated to 100° and an interpass

Table 1 Welding parameters

Parameter	Value
Wire feed rate	6.5 m/min
Arc voltage	25 V
Welding current	206 A
Welding speed	300 mm/min
Energy input per unit length	1.03 kJ/mm
Shielding gas	DIN EN ISO 14175: M20-ArC-15

temperature of 100 °C was also kept between the individual welds. The wire electrodes were welded in this way to allow a high number of samples to be taken from the weld metal. The

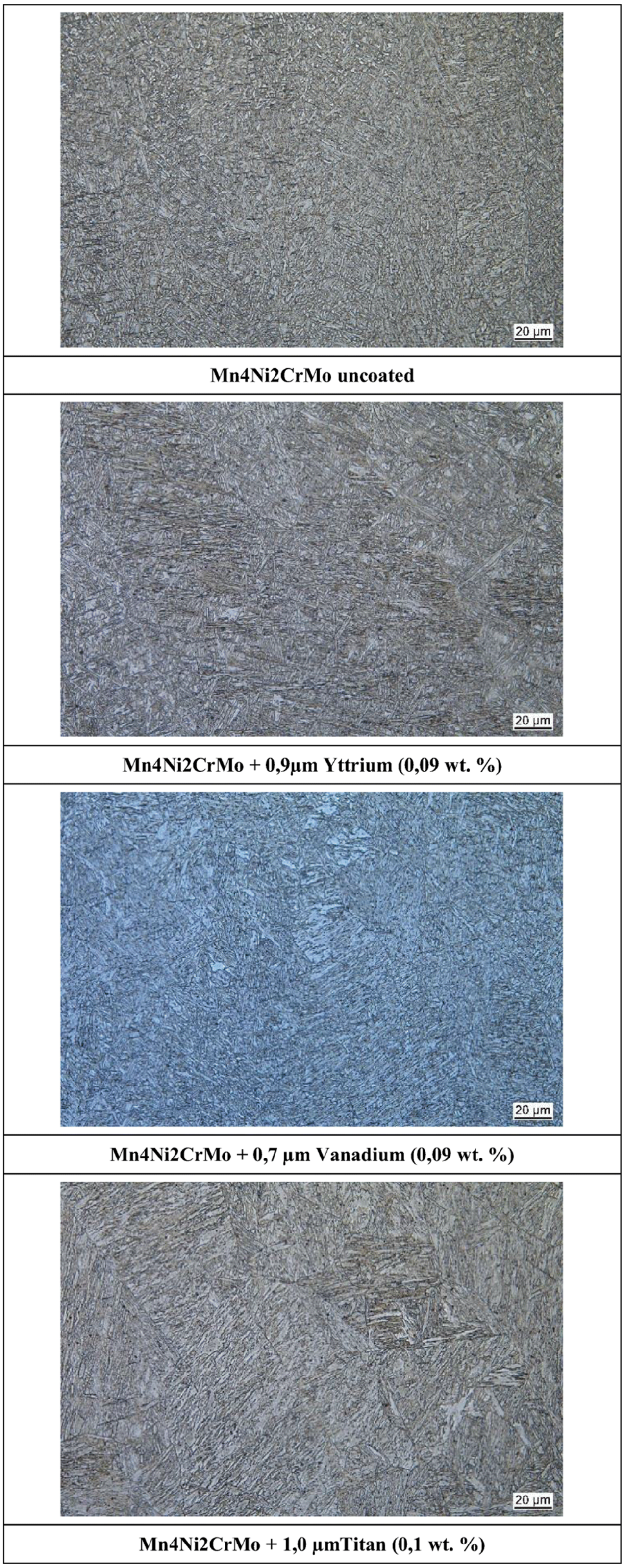

Fig. 3 Micrographs mono-element coatings

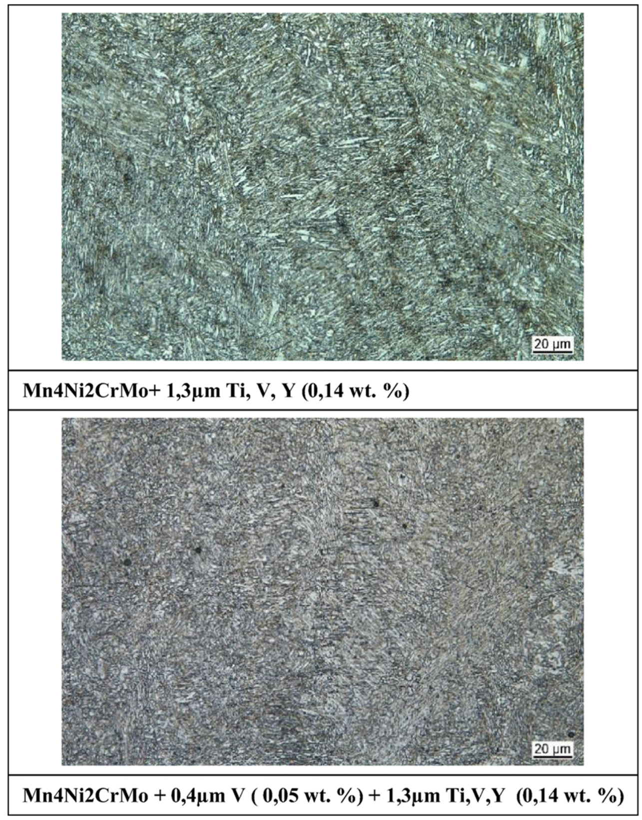

Fig. 4 Micrographs multi-component coating and multilayer coating

procedure was chosen, even if losses in strength are to be expected compared with the procedure according to DIN EN ISO 15792-1, since the focus of the tests was on the pure weld metal without dilution.

Both the processing of these uncoated and later also the coated wire electrodes was carried out with the parameters shown in Table 1.

Fig. 2 shows the microsection of a multilayer welded blind seam from which the samples for determining the mechanical properties of the weld metal were taken. The tensile specimens

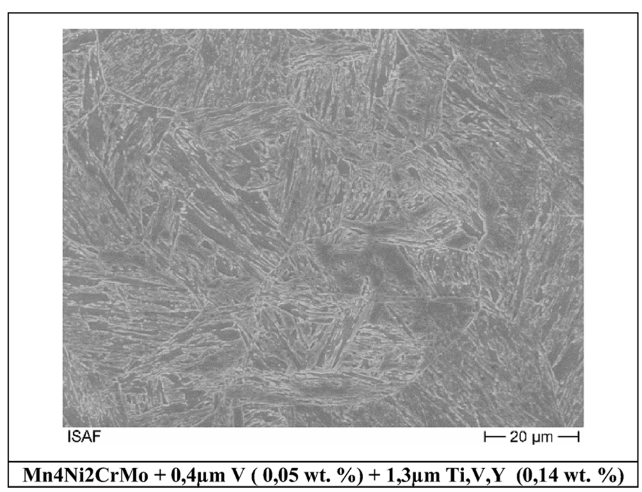

Fig. 5 Scanning electron micrograph of the weld metal structure

Table 2 Chemical composition mono-element coatings

Element	Uncoated (wt.%)	Y-coated (wt.%)	V-coated (wt.%)	Ti-coated (wt.%)
C	0.111	0.115	0.119	0.124
Mn	1.50	1.57	1.52	1.48
Ni	2.18	2.18	2.06	1.99
Si	0.736	0.760	0.714	0.698
Cr	0.319	0.344	0.362	0.358
Mo	0.559	0.573	0.556	0.546
Y	<0.0050	**0.0097**	<0.0050	<0.0050
V	0.0022	0.0044	**0.0065**	**0.0083**
Ti	0.0350	0.150	0.0392	0.0853

in accordance with DIN EN ISO 6892-1 [12] were taken in the longitudinal direction of the weld, and the specimens for the Charpy impact test in accordance with DIN EN ISO 148-1 [13] were taken transversely. In addition, microsectional samples and micrographs were taken.

2.2 Metallography

In order to visualize the influence of the different coating elements on the structure of the weld metal, the specimens were polished and etched with alcoholic nitric acid (Nital). Fig. 3 shows the weld metal of coated wire electrodes compared to an uncoated reference wire electrode (Mn4Ni2CrMo). In addition to the coating thickness, the calculated mass fraction is given. It can be clearly seen that the yttrium, vanadium, and titanium coatings increase the proportion of needle ferrite in the microstructure, which initially suggests a higher yield strength. Furthermore, grain refinement occurs due to the coatings.

In addition to single coating elements, the influence of coatings consisting of a composition of several elements was tested. For this purpose, the effects of the mono-element coatings

Table 3 Chemical composition multi-component coating and multilayer coatings

Element	Uncoated (wt.%)	Ti-, V-, Y-coated (wt.%)	V+Ti-, V-, Y-coated (wt.%)
C	0.111	0.122	0.122
Mn	1.50	1.43	1.43
Ni	2.18	1.98	2.22
Si	0.736	0.652	0.723
Cr	0.319	0.363	0.339
Mo	0.559	0.541	0.581
Y	<0.0050	**0.0227**	**0.0216**
V	0.0022	**0.0379**	**0.124**
Ti	0.0350	**0.0876**	**0.0927**

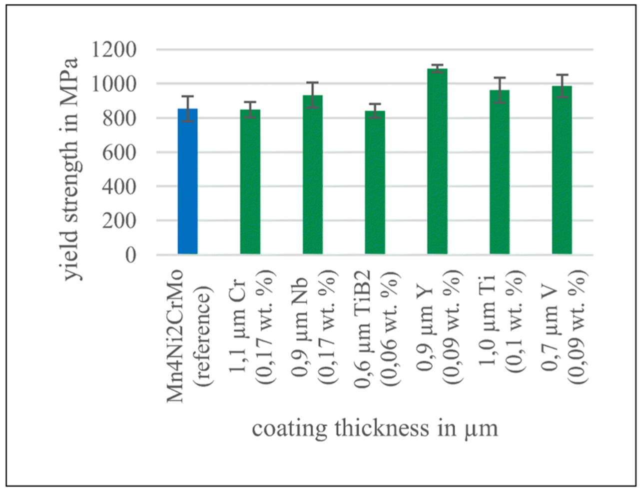

Fig. 6 Effects on the yield strength by various coating elements

on the weld metal were evaluated in an influence matrix. In order to further increase the strength, multi-component and multilayer coatings were developed, which are composed of the tested individual components. The microstructure of the weld metal of a welding wire electrode coated with the elements titanium, vanadium and yttrium (multi-component coating) is shown in Fig. 4. The coating has reached a thickness of 1.3 µm. Fig. 4 also shows the structure of a welding wire electrode on which a 0.4-µm-thick vanadium layer was deposited and a second layer of titanium vanadium and yttrium on top, resulting in a total layer thickness of 1.7 µm. Also here, the given mass fractions are calculated values.

An electrode with a pure vanadium coating shows increased spattering during processing and a correspondingly poor weld seam quality. In order to take advantage of the significant increase in strength due to the increase in vanadium

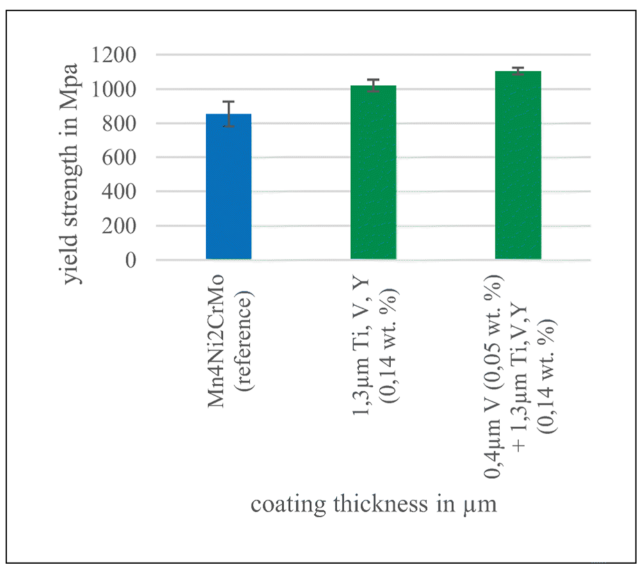

Fig. 7 Effects on the yield strength by multi-component coating and multilayer coatings

Table 4 Results of the tensile tests

Coating	Coating (wt.%)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
Mn4Ni2CrMo (uncoated)	–	855	1055	19
Cr	0.17	849	963	19
Nb	0.17	934	1123	20
TiB2	0.06	842	1025	12
Y	0.09	1087	1150	6
Ti	0.1	963	1149	17
V	0.09	986	1267	15
Ti, V, Y	0.14	1022	1141	16
V+Ti, V, Y	0.05	1105	1184	17
	0.14			

content and, at the same time, to process the electrode in a process-stable manner, several layers were applied on top of each other (multilayer coating).

For a more detailed examination of the weld metal structure, a SEM image was taken, which is shown in Fig. 5. A martensitic microstructure can be seen. The mechanical properties of the microstructure are described in Section 2.3.

Studies describing the material transition from the coating to the weld metal are still pending. Micrographs at various positions indicate that the influence on the microstructure is uniform. Inductively Coupled Plasma–Optical Emission Spectrometry (ICP-OES) was carried out to prove material transfer from the coating to the weld metal. Table 2 shows the chemical composition of the respective weld metal including the coating elements.

It can be clearly seen that, compared to the reference weld metal, the respective element content can be increased by applying a coating. However, the determined values are lower than the calculated mass fractions, which is due to combustion in the arc. The vanadium content is higher in the weld metal of the Ti-coated wire electrode than in the weld metal of the V-coated one. Investigations regarding the influence on the arc by a V-coating and the combustion are still in progress.

The transition of the multi-component coating as well as the multilayer coatings was also investigated by performing ICP-OES analyses.

Table 3 shows the chemical composition multi-component coating and multilayer coatings. Here, the transition of the coating elements into the weld metal can also be verified.

2.3 Mechanical properties

The effects on the yield strength of the weld metal caused by various coating elements are summarized in Fig. 6. The coating elements titanium, vanadium, and yttrium lead to a significant increase in the yield strength of the weld metal. By sputtering a coating of 0.9 μm yttrium, the yield strength can be increased from 855 to 1087 MPa and thus by 27%. This increase represents the maximum in the tests with individual coating elements. Vanadium and titanium also significantly increase the yield strength. With a titanium coating, the yield strength can be increased by 13% in a reproducible manner. The vanadium coating raises the yield strength by 15%.

Fig. 7 compares the strengths of the microstructures and alloy compositions shown in Fig. 4 with the reference weld metal. The electrode with multi-component coating achieves only a 20% increase in strength compared to the reference electrode. In contrast, the electrode with an additional vanadium coating (multilayer system) achieves a strength increase of 30%.

Table 4 shows the yield strength, tensile strength and elongation at break in relation to the respective coating. The experiments were performed at room temperature.

In addition, the ductility of the weld metal is affected when coated electrodes are processed.

Compared to the uncoated reference wire electrode, the coated electrodes show a significantly lower impact energy at room temperature. The reproducible yield strength achieved in the tests represents a significant further development compared with the state of the art (Table 5).

2.4 Influencing the welding process

The wire electrode coating influences not only the properties of the weld metal but also those of the welding process.

Table 5 Impact energy of the weld metal

Wire/coating	Impact energy (J)
Mn4Ni2CrMo (reference)	70
0.9 μm Y (≙ 0.09 Gew.%)	17
1.0 μm Ti (≙ 0.1 Gew.%)	51
0.7 μm V (≙ 0.09 Gew.%)	44

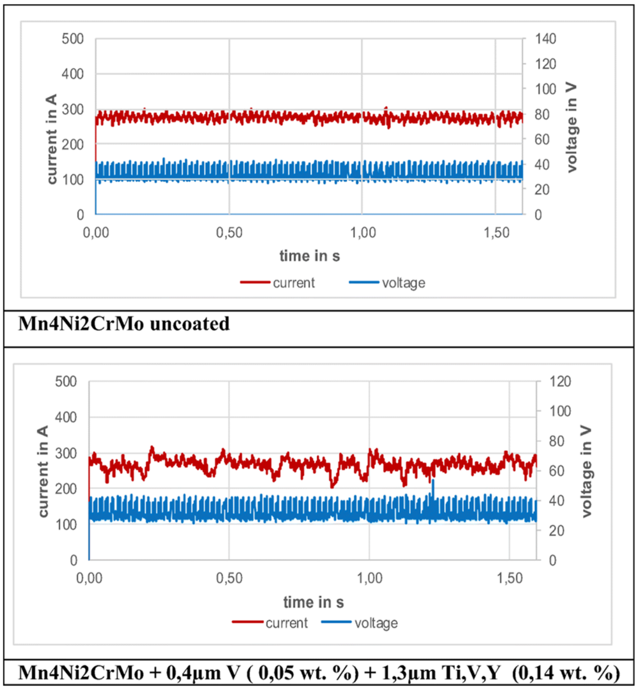

Fig. 8 Energy consumption of the welding process

High-speed videos of the arc were made to analyze the welding process. In addition, current and voltage were measured during the welding process, thus documenting the energy consumption of the weld. Fig. 8 shows the curve of current and voltage during the welding process.

The energy absorption of the compared welds is at the same level. The coating elements evaporating in the arc cause changes in the arc plasma. The changes of the plasma lead to a change of the arc and perspective of the arc length. This is evident in the high-speed images of the arc.

3 Summary

By coating GMAW wire electrodes in the PVD process, the weld metal structure and thus also the weld metal strength can be influenced to a large extent. In particular, it is possible to introduce grain-refining elements into the weld metal. The strength of the weld metal can be increased by up to 30% via coating systems. Multilayer coatings offer the possibility to adjust the weld metal strength and the welding process almost separately. Grain-refining and strength-increasing elements can also have a negative effect on the processing properties if they are used as an outer layer. These can be covered with process-stabilizing coating elements. With the coating of a Mn4Ni2CrMo welding wire electrode, a reproducible average yield strength of 1105 MPa at an impact energy of 37 J can be achieved. This represents a significant advance over the current state of research.

4 Outlook

The material transition from the wire electrode to the weld metal must be investigated in detail. On the one hand, the transition of the coating into the weld metal and, on the other hand, the burnup of the coating in the arc must be studied in more detail.

Acknowledgments The investigations presented were supported within the framework of the Central Innovation Program for SMEs (ZIM) by the Federal Ministry for Economic Affairs and Energy on the basis of a resolution of the German Bundestag (grant number: ZF4419001FH7). We thank the Hermann Fliess GmbH & Co KG and the SSAB Swedish Steel GmbH for the support of the investigations.

Funding Open Access funding enabled and organized by Projekt DEAL.

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