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RESEARCH PAPER

Development of high-strength welding consumables using calculations and microstructural characterisation

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Abstract

The development of new welding consumables requires several samples and experiments that must be performed to achieve the required mechanical properties. In the development of a metal-cored wire with a target tensile strength of 1150 MPa and acceptable impact toughness, thermodynamic and kinetic calculations via MatCalc were used to reduce the experimental work and the resources required. Micro-alloying elements were employed to obtain high strength as an alternative approach to conventional solid solution hardening. Investigations of the microstructure were performed via atom probing to understand the effects of micro-alloying elements. In particular, the influences of different elements on the precipitation behaviour in the weld metal were evaluated. The calculated mechanical properties are in accordance with the results obtained from experiments and can be explained by microstructural investigations. The approach is exemplified through vanadium and clarifies an efficient development route.

Keywords Alloy development · filler materials · high-strength steel · metal-cored wire

1 Introduction

Lightweight components are essential nowadays to meet the need for reduced energy consumption. High-strength steels represent a decisive part of the framework of these concepts. On the one hand, they fulfil the requirements for construction with reduced weight, high strength and acceptable toughness. On the other hand, they meet the demands for carrying high loads. Applications range from the transportation and lifting sector (like cranes) to the energy sector, e.g. pipelines.

High-strength steels with yield strength higher than 1100 MPa already exist. Welding consumables for gas metal arc welding reach their limits at yield strength above 960 MPa and in standards, they are defined only up to 890 MPa. Therefore, these high-strength steels must be welded with under-matching filler material and hence, their superior mechanical properties cannot be exploited.

The development of welding consumables is a time and manpower/resource-intensive process. Thus, this work was conducted with the intention of acquiring methods and knowledge to shorten and facilitate future developmental work.

The target was to develop a metal-cored wire with yield strength of 1100 MPa and toughness of 47 J at a temperature of −20 °C. Metal-cored wires offer the advantages of high productivity and good penetration behaviour. A structured approach was used for the development of the alloy design. Single elements were varied in fine adjustment with the target to find the optimal balance between strength and toughness. Due to the high number of raw materials in the metal-cored wire, various complex interactions occur between the components.

Most previous research concentrated on HSLA steels with an acicular ferritic or bainitic microstructure [1–3]. The alloy composition in this work possesses a martensitic microstructure.

Micro-alloying elements were used to fulfil the balance between strength and toughness. Micro-alloyed steels also

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offer excellent weldability, which is attributed in part to the presence of nanosized carbide and carbonitride precipitates [4]. Fine adjustments of these elements result in major changes to the mechanical behaviour. MatCalc calculations and microstructural investigations were used to understand the effects of the elements in alloy design. The martensitic microstructure has already been characterised through different etching methods and was described in [5]. Atom probe tomography is used to explain possible strengthening effects and their influence on toughness.

Elements such as Ni, Mn, Mo, Ti, Al, V and B were used in the high-strength alloy design. Ni and Mn play important roles in high-strength steel weld metal compositions. Keehan et al. reported that high contents have positive effects on strength, but negative effects on toughness, attributed to relatively low Ac_1 and Ac_3 temperatures, which give less tempering [6]. They observed that the causes show interdependence [7]. The strengthening effect of Ni is considered to be due to solid solution strengthening and the loss in toughness due to coarsening effects [8]. Keehan et al. reported that toughness decreases when the amount of Ni exceeds a certain level, depending on the level of Mn [7]. Different roles of Mn are described in the literature. On the one hand, it can cause grain coarsening and influence the toughness in a negative way [9]. On the other hand, it was observed that Mn helps to refine and homogenise the weld microstructure [10]. Bhole et al. reported that Ni and Mo affect the impact toughness positively due to microstructural factors [11]. Adding Mo and Ni together can both improve and decrease the toughness [11, 12]. C promotes martensite formation resulting in a stronger microstructure and the accompanied refinement of microstructure engenders an acceptable toughness [13]. Evans et al. and Beidokhti et al. found that Ti concentrations of 0.02 and 0.05 wt% produce weld metals with high strength and toughness [10, 14]. In combination with B, Ti can generate a fine microstructure due to the pinning effect of boron nitride and titanium carbonitride [15]. A similar effect is caused by V in combination with N [16, 17]. Evans et al. and Vanosek et al. reported that a low Al content leads to high values of tensile strength and toughness [18, 19]. The optimal range of size distribution of inclusions and the correlated grain refinement seem to be essential for a good balance of high strength and toughness [16, 17, 20–22].

The strengthening effect of micro-alloying elements is based on fine carbonitride particles, grain refinement due to particles that remain undissolved in austenite, or precipitates that are formed. The nitrides of micro-alloying elements are more stable than carbides in austenite and their solubilities differ significantly, which is particularly the case for V and Ti. In general, the solubility of V(C,N) is much larger than that of other micro-alloying elements (Fig. 1). Vanadium carbide will be completely dissolved even at low austenitising temperatures. Nitrides are substantially less soluble than their corresponding carbides. The solubility product of VN is two orders of magnitude lower than that of VC, which implies that N has a crucial role in the enhancement of the driving force for precipitation. V precipitates as pure nitride in austenite until nearly all the N is consumed. During the γ-α transformation, N-rich vanadium carbonitrides may precipitate as a result of the solubility drop of vanadium carbonitrides associated with the transformation. TiN is extremely stable up to high temperatures. Due to its low solubility product, it shows the greatest potential for precipitation. Niobium carbides and nitrides offer low solubilities and may precipitate in later stages [23, 24].

One of the objectives in the scope of development was to explore the effect of V within a high-strength alloy composition. Additionally, the paper aims to point out possibilities supporting the development of welding consumables and to

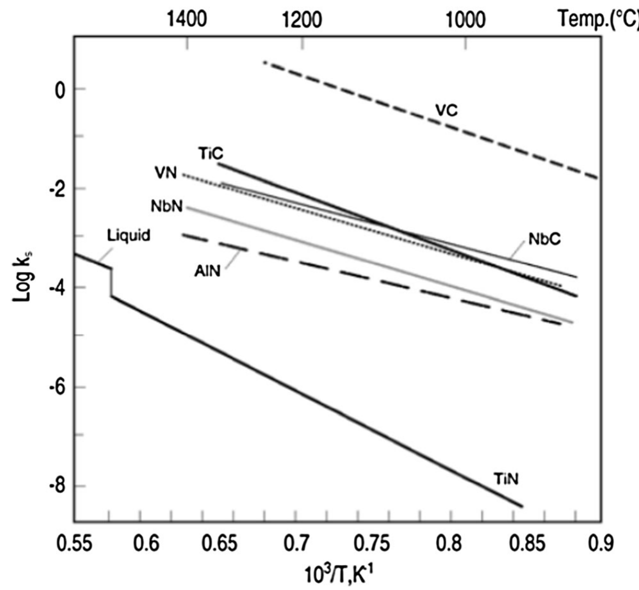


Fig. 1 Solubilities of micro-alloy carbides and nitrides [23]

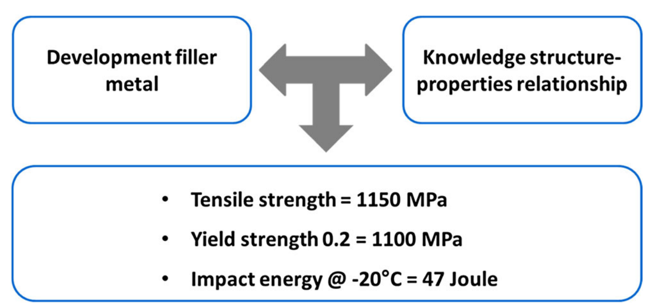


Fig. 2 Goals for development of metal-cored wire

Table 1 Welding parameters used for the production of all-weld metal samples

Current [A]	Voltage [V]	Welding speed [mm/min]	Heat input per unit length [kJ/mm]	Interpass temperature [°C]
250	26.5	550	0.71	150

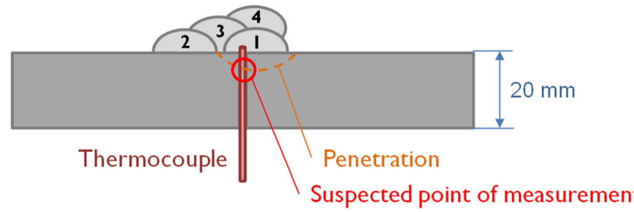


Fig. 3 Measurement of heat cycle [25]

derive advantages from the created knowledge for further developments. The goals are summarised in Fig. 2.

2 Materials and methods

Metal-cored wires with different compositions were produced and the samples were welded. All-weld metal samples were prepared in accordance with EN ISO 15792-1 at flat PA using Ar + 18% CO_2. They were produced with eight weld passes and three beads each. The welding parameters are shown in Table 1. S235 was used as the base material and three layers were applied as the buffer.

The welded samples for mechanical testing were subjected to soaking heat treatment at 150 °C for 16 h as per EN ISO 15792-1. Tensile and Charpy-V impact toughness testing were performed on the all-weld samples. The tensile tests were carried out on single specimens and performed at ambient temperature in accordance with EN ISO 6892-1. The impact tests were conducted on three samples to obtain a set for statistical interpretation. Impact tests of samples were performed at ambient temperature and − 20 °C, defined by EN ISO 9016.

Numerical simulations were performed using the thermokinetic package MatCalc 5.61 (rel. 1.003) or a newer version. The thermodynamic database used was v2.029 and the diffusion database was v2.006. The basis for the calculation was virtual heat treatment representing the welding process. A thermocouple was placed between two 20-mm thick plates and the heat cycle was recorded, as depicted in Fig. 3.

The resulting virtual heat treatment is illustrated in Fig. 4. The first slope is caused by the welding of bead one and the following peaks arise from additional weld passes.

Five different strengthening mechanisms were considered for their contributions to the overall yield strength: solid solution strengthening, precipitation strengthening, grain boundary strengthening, dislocation hardening and intrinsic lattice strength.

Different alloy designs were proposed after simulation via MatCalc. Three of them were produced and tested for their mechanical properties (Table 3).

Atom probe tomography (APT) was utilised for in-depth examination of the high-strength all-weld samples. For APT analysis, rods with a cross section of 0.3×0.3 mm^2 were cut longitudinally from the material at random locations at the centre. They were electropolished and mounted in a Cameca LEAP 3000X HR. The samples were run in laser mode at a specimen temperature of 60 K, with 250 kHz pulses and laser energy of 0.3 nJ. The APT data were evaluated using a Cameca IVAS 3.6.8.

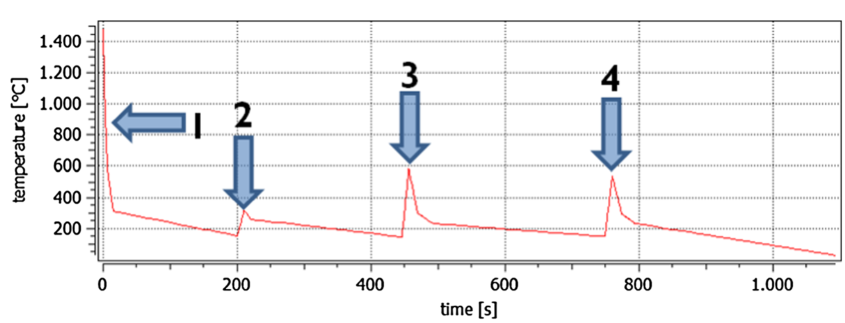
3 Results

3.1 Alloy design development

More than 120 samples with different alloy compositions were investigated and the influences of certain elements on the mechanical properties were examined and analysed.

The results are depicted in Fig. 5. The red lines indicate the required strength and toughness and the shaded area illustrates the target field. Two alloy designs reach the requirements regarding strength and toughness. It is obvious that a vast

Fig. 4 Virtual heat treatment for simulations with MatCalc resulting from thermocouple measurements [25]



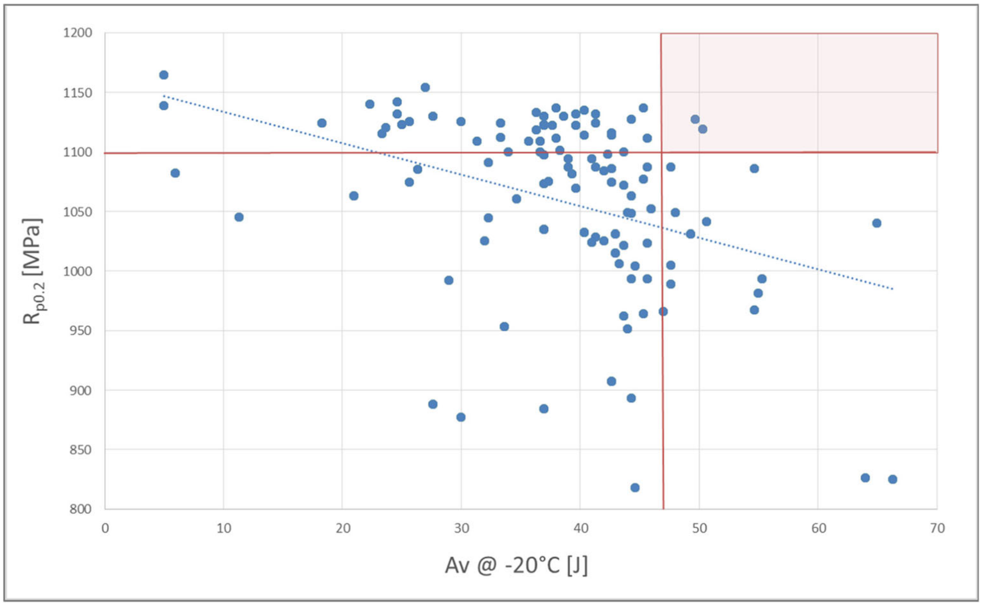


Fig. 5 Experimental strength versus toughness at − 20 °C of tested metal-cored wires

number of samples are necessary for obtaining the right balance between the mechanical properties. Certain elements cause strength increase but affect the toughness in a negative way, for instance Nb. On the other hand, the reduction of elements such as Mn or Si results in high toughness though the strength decreases due to the missing effect of solid solution strengthening. Some exemplary results of these investigations are summarised in Table 2. The reasons for the effects of the mentioned elements are not discussed to their full extent within the scope of this paper.

Table 2 Exemplary results of testing the influence of elements on mechanical properties

	YS [MPa]	Av (− 20 °C) [J]
0.11% Cr	825	66
0.37% Cr	944	55
0.55% Cr	1059	48
0.7% Cr	1180	44
0.98% Cr	1142	25
170 ppm Ti	1021	36
260 ppm Ti	1048	39
75 ppm N	1032	40
150 ppm N	1035	37
300 ppm N	1140	22
75 ppm N, 250 ppm Ti	1074	26
150 ppm N, 250 ppm Ti	1085	26
300 ppm N, 250 ppm Ti	1120	24
200 ppm Ti, 15 ppm B	1028	41
200 ppm Ti, 27 ppm B	1025	32
200 ppm Ti, 660 ppm Nb, 0 B	1063	41
200 ppm Ti, 660 ppm Nb, 27 ppm B	1045	32
1.16% Cu	953	10
2.75% Cu	–	6

More than 15 raw materials are part of the alloy design. Complex interactions occur between the components and the multiplicity of interrelations complicates the structured approach.

Cr is beneficial to strength but detrimental to toughness, as depicted in Table 2. A certain content of Cr is necessary for strength; therefore, an accurate balance between strength and toughness is important.

The augmentation of Ti results in a modest increase in the toughness and stable strength.

An increase in the N content from 75 to 150 ppm does not significantly affect the properties. Further augmentation to 300 ppm leads to a tremendous decrease in the toughness, but a slight increase in strength. Samples with 500 ppm N could not be welded due to pore formation.

On the basis of the pinning effect described in the literature, Ti and B were added in a ratio of approximately 10:1, which resulted in high toughness at a low B content, but the yield strength did not fulfil the requirements. The desired grain refinement due to the addition of Nb did not result in the enhancement of the properties. The addition of Cu resulted in a drop in toughness.

Many variations of elements are possible and their testing comes with tremendous effort. Therefore, facilitation of the development's process is worthwhile. One approach is the use of thermodynamic and kinetic simulations via MatCalc to reduce the effort. The effects of different alloying elements on the total yield strength can be understood and assessed by

Table 3 Three alloy compositions were proposed to increase strength

[m.%]	C	Si	Mn	Σ (Cr + Ni + Mo)	V	Al	Ti	Nb	N
Alloy 1	0.12	0.8	2.6	4.0	–	0.03	0.03	0.08	0.016
Alloy 2	0.12	0.8	2.6	4.0	0.3	0.03	0.03	0.08	0.016
Alloy 3	0.12	0.8	2.6	4.0	0.5	0.03	0.03	0.08	0.016

MatCalc, which is discussed in the following section with the example of V-alloyed samples.

3.2 MatCalc calculations for V-alloyed samples

Three different compositions were proposed on the basis of MatCalc calculations containing Al, Ni, Nb and varying contents of V with the objective of maximising strength, see Table 3, whereby the cumulated percentage is in following range: Cr 0.5–0.8, Mo 0.5–0.8 and Ni 2.5–3.0. Al was added to increase strength by precipitation and prevent grain growth owing to its pinning effect. The increase of Al leads to a reduction of N in solution. This decrease in solid solution strengthening is compensated for by the gain in precipitation strengthening due to the large volumetric misfit [26]. Ti is added owing to its role as a nucleus and a grain growth inhibitor. Nb should decrease the grain size, retarding recrystallisation by a solute drag mechanism at the recrystallised grain boundary. Nb stays in the solution within the lattice [26].

3.3 Chemistry and mechanical properties

The chemical analysis results of the metal-cored wires produced on the basis of the proposed alloys are shown in Table 4. Slight deviations from the proposed composition may result from variations in raw materials and processing procedure.

The mechanical properties of the alloys and the comparison between measured and calculated values can be found in Table 5 and illustrated in Fig. 6. An increase in the V content to 0.3% resulted in the augmentation of the yield strength. A further increase to 0.5% did not significantly improve the strength or affect the toughness. An acceptable accordance was accomplished between measured and calculated strength values. The calculation overestimates the yield strength for each of the three tested samples. In the cases of alloys 2 and 3, the calculated values differ by 10% from those determined experimentally. The values of alloy 1 agree to an accuracy of 15.6%. However, the trend of higher strength with increasing V content was predicted correctly.

This accuracy is adequate considering the number of influences, both on the calculated values and on the measured ones. On the one hand, the chemistries of the samples are not completely identical to those proposed. On the other hand, variations due to the production procedures must also be considered. Additionally, the mechanical properties were obtained by a single measurement each, which may also signify another influencing factor.

The contributions of the strengthening mechanisms to the total yield strength are depicted in Table 6.

The loss in solid solution strengthening is more than that compensated for by the gain in precipitation and grain boundary strengthening, depicted in Table 6 and Fig. 7. The largest share of strength is due to dislocation strengthening, which remains at 516 MPa in all three samples and is therefore not influenced by the V content.

It can be seen from the corresponding phase fractions diagram (Fig. 8) that with increasing V content, the phase fraction of V(C,N) increases, whereby the amount of TiN decreases. Small shares in the primary phases belong to NbN and NbC, which remain nearly at constant levels.

Table 4 Chemistry of produced alloys 1–3, measured by optical emission spectroscopy

[m.%]	C	Si	Mn	V	Al	Ti	Nb	N
Alloy 1	0.08	0.8	2.5	–	0.02	0.04	0.08	0.005
Alloy 2	0.09	0.9	2.5	0.3	0.03	0.04	0.08	0.005
Alloy 3	0.08	0.8	2.5	0.5	0.03	0.04	0.08	0.005

Table 5 Mechanical properties of the alloys 1–3, including comparison to calculation

	R_m [MPa]	$R_{p0.2;measured}$ [MPa]	$R_{p0.2;calculated}$ [MPa]	Difference [%]	Av 20 °C [J]	Av − 20 °C [J]
Alloy 1	1204	1082	1251	15.6	17	7
Alloy 2	1268	1139	1260	10.6	9	5
Alloy 3	1272	1164	1282	10.1	6	5

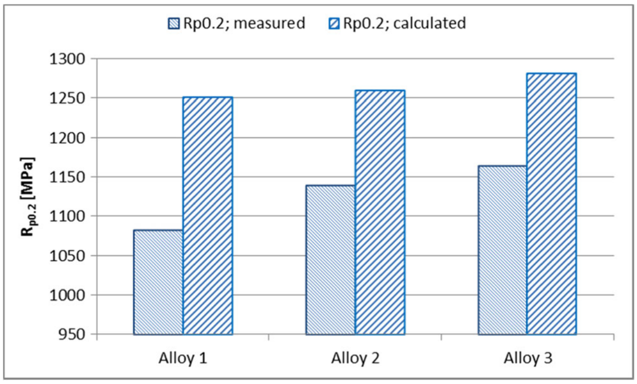


Fig. 6 Comparison of measured and calculated yield strengths

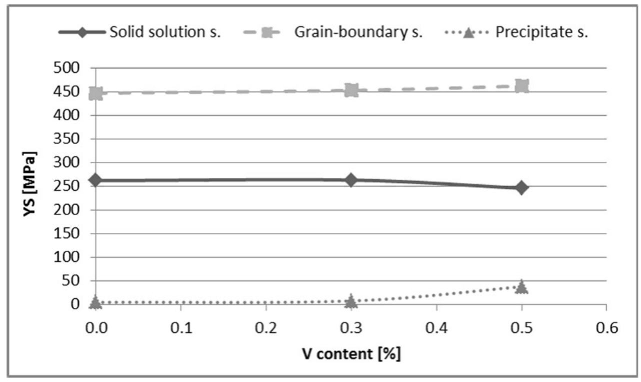


Fig. 7 Contribution to total yield strength with varying V content

3.4 Microstructural characterisation

Atom probe tomography revealed the clustering effect of V and disclosed precipitates with sizes of 1–10 nm. The compositions of the precipitates, listed in Table 7, changed slightly with an increasing amount of V. In the case of alloy 1, the precipitates consisted of Ti, Nb, N and C. A large part of Fe was dissolved in the particles. Alloy 2 offered precipitates with V and more N and C, but less Ti, which agrees with the MatCalc results showing that an increased V content leads to lower TiN precipitates compensated by VCN. A further rise in V did not affect the composition of the precipitates but caused larger particle sizes. Al was not present in the precipitates due to its homogeneous distribution [27].

An exemplary illustration of a reconstructed atom probe measurement is depicted in Fig. 9. The pink dots represent iron atoms and the blue areas indicate enrichments in V, N, C and Ti. The chemical composition inside the precipitates was quantified by analysing the exported particles.

Further and more detailed investigations of precipitate evolution in all-weld metal can be found in [27].

Table 6 Contributions of strengthening mechanisms to total yield strength

	Total YS [MPa]	Solid Solution s. [MPa]	Dislocation s. [MPa]	Grain boundary s. [MPa]	Precipitate s. [MPa]
Alloy 1	1251	262	516	447	5
Alloy 2	1260	263	516	453	8
Alloy 3	1282	246	516	462	38

4 Discussion

The objective of this paper was to demonstrate how laborious the development of welding consumables can be, particularly when investigating the balance between high strength and acceptable toughness. It is necessary to investigate the effects of single elements and their interactions within an alloy design to find the ideal content of each component of the composition. Furthermore, complex interactions and reactions during welding impede development. The large number of samples necessary for a structured approach implies resources and intensive investigation. Therefore, thermokinetic calculations and microstructural investigations can support development and establish information regarding the mechanisms responsible for the properties. This was shown by varying the V content of an alloy.

With the aid of MatCalc, the yield strength of an alloy design containing Al, Ti and Nb was calculated and the effect of V on strength was simulated. The addition of V results in higher yield strength. The tendency was confirmed by experimental investigation, even though the model overestimated

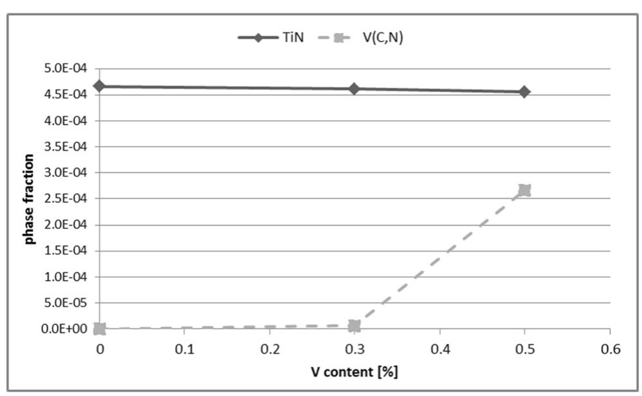


Fig. 8 Simulated phase fractions of precipitates with varying V content in the all-weld metal

Table 7 Average chemical composition of precipitates in at%. The rest is attributed to matrix elements [27]

Element	Alloy 1	Alloy 2	Alloy 3
Ti	22 ± 10	15 ± 4	17 ± 4
Nb	6 ± 2	8 ± 4	7 ± 1
V	–	18 ± 2	19 ± 6
N	7 ± 4	15 ± 4	20 ± 4
C	15 ± 13	19 ± 4	17 ± 4
Fe	40 ± 8	14 ± 3	12 ± 4
Precipitate size	1–5 nm	5 nm	10 nm

the strength. The change in strength contributions showed the impact of augmenting V in the alloy.

The increase in V affects the strength in a positive way and reduces the toughness slightly. V is found to have a strong effect on strength due to its affinity for N and C. The strengthening effect of V is based on higher precipitation and grain boundary hardening mechanisms. However, solid solution strengthening is reduced due to the lower amount of N in solution (because it is bound in V(C,N) clusters). This is more than compensated for by the other two mechanisms. Due to the higher affinity of N for V there is less N left to form TiN, which resulted in lower content of TiN precipitates. It is supposed that V provokes grain refinement because higher proportion of grain boundary strengthening has been calculated.

Atom probe tomography confirmed that the strengthening mechanism was by precipitation and relies on fine carbonitride particles with a size of 1–10 nm. The small sizes of the V(C,N) clusters cause a minute reduction in toughness, although the strength is improved. It was shown that N plays a crucial role in the alloy because the amount of this element in the precipitates of alloys 2 and 3 increases significantly. A lower amount of Ti and a higher amount of V in the precipitates of alloys 2 and 3 signify certain changes in the composition of the precipitates correlating to the chemistry of the metal-cored wires. This is in accordance with the calculations via MatCalc, which depicted a significant increase in V(C,N) particles and slight decrease in TiN.

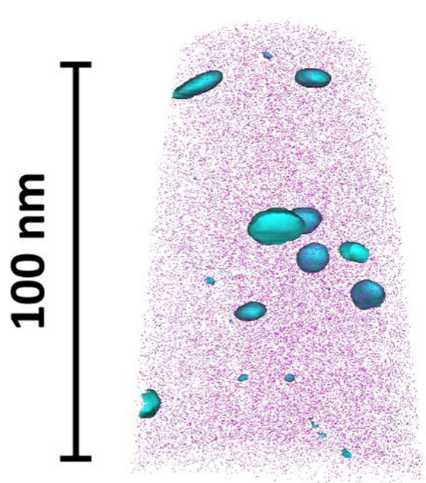


Fig. 9 Atom probe reconstruction of alloy 3

5 Summary

The development of welding consumables is a time- and resource-consuming process. This process can be supported by MatCalc modelling and microstructural characterisation to create better knowledge and to understand the mechanisms that lead to certain properties. Within the framework of this paper, this was demonstrated by three micro-alloyed samples which varied in their V content. It was revealed that an increasing amount of V results in improved strength. One of the causes found via MatCalc and APT investigations is the formation of V(C,N) precipitates with a size of up to 10 nm. The focus was set on strength; however, toughness is a property that cannot be neglected and has to be considered as a decisive factor in high-strength welding consumables.

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