Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Weldability of Low-Manganese Filler Metals: Mechanical Properties and Solidification Cracking in MAG Welding

Lauriane Guilmois

lauriane.guilmois@cetim.fr

CETIM: Centre Technique des Industries Mecaniques https://orcid.org/0009-0005-7593-7740

Simon Pigaux-Leys

CETIM: Centre Technique des Industries Mecaniques

Laurent Jubin

CETIM: Centre Technique des Industries Mecaniques

Research Article

Keywords: Low-manganese filler metals, MAG welding, Solidification cracking, Weld mechanical properties, Flux-cored consumables, Metal-cored consumables

Posted Date: November 13th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11202427/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Weldability of Low-Manganese Filler Metals: Mechanical Properties and Solidification Cracking in MAG Welding

L. Guilmois[1,a] (corresponding author)**, S. Pigaux-Leys** [1,b]**, L. Jubin**[1,c]

[1] Centre Technique des Industries Mécaniques (CETIM), 52 avenue Felix Louat, 60300 Senlis, France

[a]lauriane.guilmois@cetim.fr, [b]simon.pigaux-leys@cetim.fr, [c]laurent.jubin@cetim.fr

https://orcid.org/0009-0005-7593-7740

Abstract

The reduction of the occupational exposure limit for manganese to 0.05 mg/m^3 in 2019 has led to the development of low-manganese filler metals designed to reduce fume emissions during welding. These consumables typically compensate for the lower manganese content through increased carbon levels and the addition of alloying elements, which may modify the microstructure and mechanical behaviour of the weld metal. In addition, reducing manganese content could affect resistance to solidification cracking.

This study investigates the weldability of low-manganese flux-cored and metal-cored filler metals compared with conventional consumables. Mechanical properties and hot-cracking susceptibility are evaluated as a function of welding parameters. Welded joints were produced using two configurations. First, butt welds were manufactured at two heat inputs (1 and 2 kJ/mm) to assess tensile properties, hardness and Charpy V impact toughness in a low-dilution fusion zone. Second, a round-bar-through-plate test was used to determine the critical welding speed associated with solidification cracking at a heat input of 1 kJ/mm.

The results show that reducing manganese content has a limited effect on tensile properties, although a slight decrease in strength is observed. Impact toughness is comparable for metal-cored wires but reduced for low-manganese flux-cored wires. Increasing heat input decreases strength but can improve toughness for low-manganese metal-cored consumables.

Regarding solidification cracking, no significant influence of manganese content is observed for C35 steel, whereas for S355 steel, the use of low-manganese wires leads to a reduction in critical welding speed.

Overall, low-manganese filler metals provide weldability comparable to that of conventional consumables under most conditions but may limit performance in applications requiring high toughness or high welding speeds.

Keywords: *Low-manganese filler metals; MAG welding; Solidification cracking; Weld mechanical properties; Flux-cored consumables; Metal-cored consumables*

1 Introduction

Welding processes generate fumes due to the high temperatures reached during melting. These fumes, which may be inhaled by operators, consist of gases and fine particulate matter capable of penetrating the alveolar region of the respiratory system. In particular, these particles are mainly oxides and have been classified as proven carcinogens for humans since 2018 by the International Agency for Research on Cancer (IARC) [1, 2].

Moreover, previous studies [3, 4, 5] have shown that, in consumable electrode arc welding processes, fume formation is primarily governed by the vaporisation of the filler metal. As a result, the chemical composition

of the consumable largely determines that of the emitted particles. It is generally accepted that approximately 95% of welding fumes originate from the consumable, except in cases where coatings, whether intentional or unintended, are present on the base material, such as zinc, paint or oil. [1].

In this context, the eight-hour occupational exposure limit (OEL) for respirable manganese was reduced in 2019 by a factor of 20, from 1 mg/m^3 to 0.05 mg/m^3 of fumes [6]. Consequently, manganese, which was already a key element in determining compliance with exposure limits (Fig. 1), has become even more critical, reducing the additive welding fume limit value for a given fume emission rate (FER) [7].

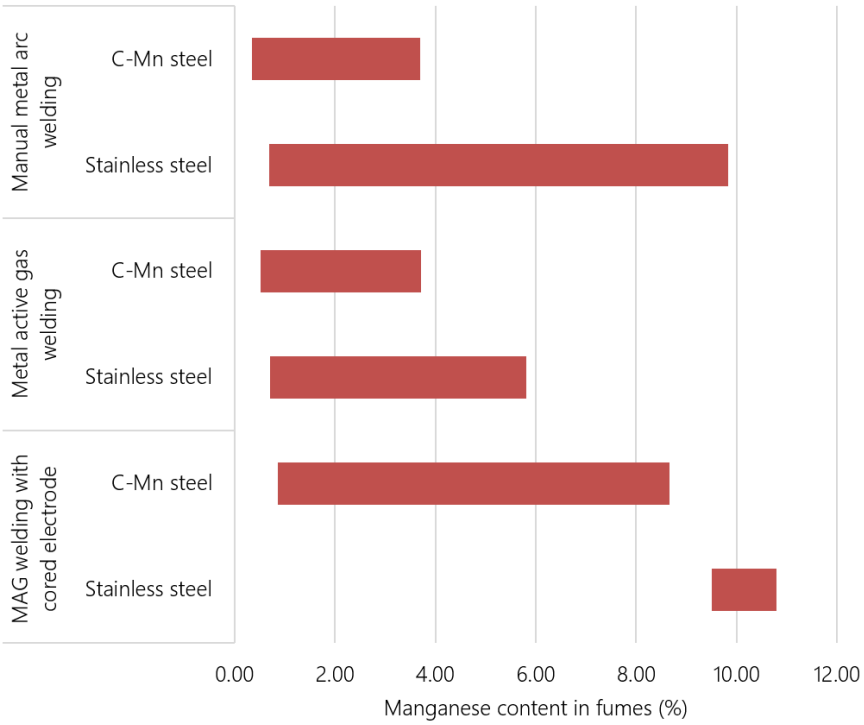


Fig. 1. Manganese content in fumes regarding the welding process (Unpublished CETIM/IS studies: Mn content corresponds to the chemical composition of the fumes sample collected according to [8, 7], filler metals are either C-Mn steels such as G3Si1:EN ISO 14341-A or austenitic stainless steels such as 308L, coated electrodes or cored wires are rutile-type, basic-type or metal cored, base metals are mostly S355 and 300-series stainless steels)

To address this constraint, manufacturers have developed consumables designed to reduce fume emissions. These wires typically exhibit modified chemical compositions, often characterised by lower carbon content and higher silicon content compared with conventional products. Earlier investigations reported that such low-fume consumables displayed behaviour broadly comparable to that of standard products from the same supplier [9].

However, following the significant reduction in manganese exposure limits, a new generation of flux-cored wires with very low manganese content has been introduced, with levels as low as 0.7% or even 0.15%. Examples are listed in Table 1. These compositions are achievable primarily with cored wires, for which only a maximum manganese content is specified, unlike solid wires where minimum values are also imposed.

Table 1. Manganese content in MAG filler metals

Filler metal, associated standard and examples		%Mn
Solid	G3Si1 [10]	1.30 to 1.60
Metal-cored	T35 à T42 [11]	≤ 2.0 (typically : 1.2 à 1.6)
	ESAB - Coreweld C6 ECO	0.74
	Voestalpine Böhler Welding - Diamondspark GUARD 420 MC	0.70
	Lincoln Electric - UltraCore Clarity M71 LE	0.13

Although the reduced manganese content is compensated by increased carbon levels and the addition of micro-alloying elements, the resulting metallurgical structure of the fusion zone is expected to be altered. Indeed, phase balance is strongly influenced by cooling rate, and modifications in chemical composition may therefore lead to significant microstructural changes Fig. 2.

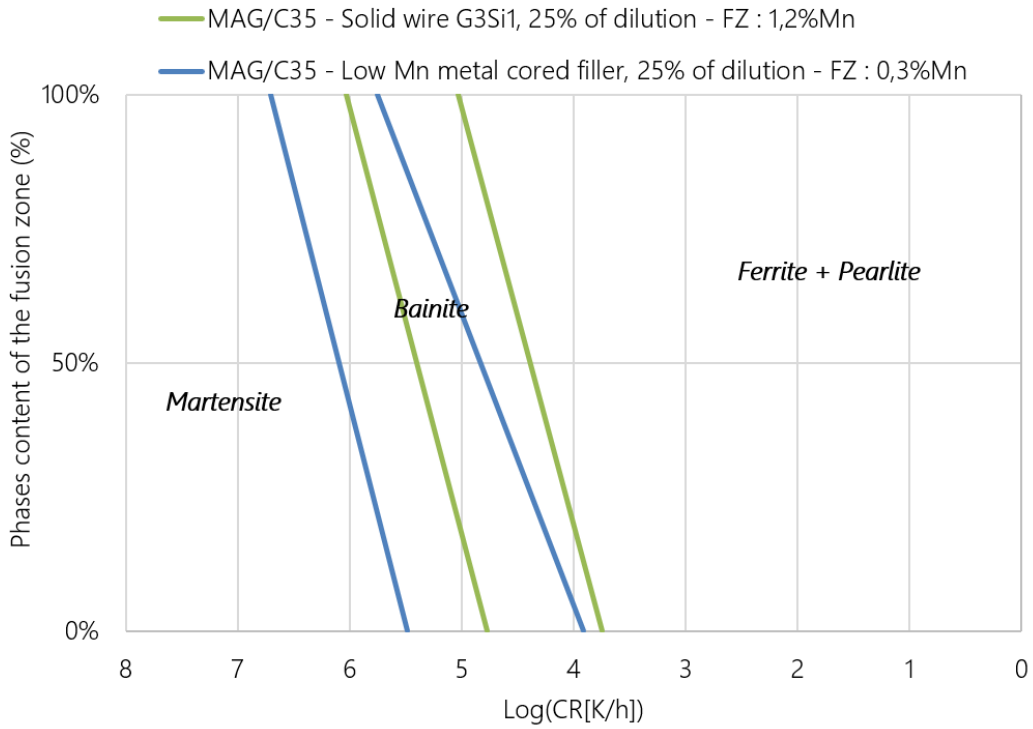


Fig. 2. Welding assembly C35 – solid wire or C35 – metal-cored filler – Dilution rate of 25 % - Estimation of phases content depending on the cooling rate at 700°C (CR in K/h) according to [12]

Against this background, the present study aims to assess the impact of welding parameters on the mechanical properties of low-fume consumables. Particular attention is paid to the effect of heat input, as higher welding energies may lead to greater degradation of mechanical properties, especially when using low-manganese wires. Furthermore, the susceptibility to hot cracking is investigated, given that manganese is recognised as an element that mitigates solidification cracking.

It should be emphasised that standard qualification procedures, whose validity range is typically limited to a 25% increase in welding energy [13], may provide a misleading indication of material performance. In practice, the thermal cycle, particularly the cooling time between 800 °C and 500 °C, plays a decisive role in determining

mechanical properties. This parameter is also strongly influenced by joint geometry and thickness, and may vary by a factor of up to six while remaining within qualification limits.

In addition, reducing the manganese content may adversely affect resistance to hot cracking. In certain cases, this could require a reduction in welding speed in order to avoid crack formation, as suggested by previous studies (Fig. 3). However, the mechanisms governing hot cracking are complex and involve multiple interdependent factors, including current, voltage, welding speed, heat input, bead geometry and chemical composition of the molten pool [12].

Nevertheless, for a given material and fixed heat input, varying the welding speed makes it possible to determine a critical value above which cracking occurs. Accordingly, the objective of this study is to evaluate whether low-manganese consumables provide a level of reliability comparable to that of standard products, particularly under conditions of high heat input.

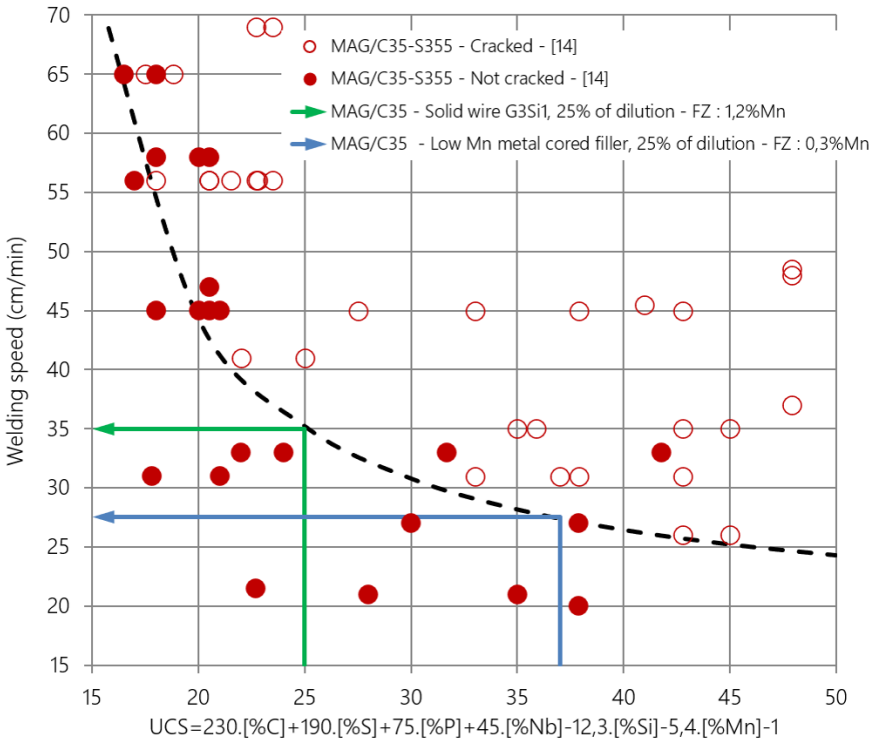


Fig. 3. Relation between critical welding speed and UCS index [14]

2 Materials and Methods

2.1 Materials

Base plates of S355J2+N steel, in accordance with NF EN 10025-2, were used as the parent material. For mechanical testing, specimens measuring 1000 × 150 × 20 mm were prepared, whereas plates measuring 200 × 200 × 20 mm were used for the assessment of hot-cracking susceptibility.

In addition, round bars of S355J2+N and C35 grades were employed for hot-cracking tests, with a diameter of 49 mm and a length of 300 mm.

Metal-cored and flux-cored filler metals with a diameter of 1.2 mm and either typical or reduced manganese content were used for metal active gas (MAG) welding. An Ar/CO_2 shielding gas mixture ([15]-M21-ArC-82/18) was employed as shielding gas.

The chemical compositions and mechanical properties of the materials are summarised in Table 2 and Table 3.

Table 2. Chemical composition of the base and filler metals according to EN 10204 3.1 reception certificate

Designation		%C	%Si	%Mn	%S	%P	%Cr	%Ni	%Cu	%Mo	%V	%B
Base metal for mechanical properties assessment and base plate for hot cracking susceptibility determination	S355J2+N [16]	0.16	0.020	0.139	0.0010	0.002	0.001	0.001	0.001	0	0.005	0
Round bar	C35 [17]	0.380	0.270	0.570	0.030	0.022	0.130	0.350	0.170	0.050	-	-
Round bar	S355J2+AR [16]	0.016	0.022	0.128	0.0017	0.0006	0.013	0.005	0.017	0.001	-	-
Typical Mn metal-cored filler metal	E70C-6M H4 [18]	0.041	0.69	1.44	0.016	0.015	0.03	0.02	0.03	<0.01	0.01	0.0003
Low Mn metal-cored filler metal	E70C-6M H4 [18]	0.04	0.59	0.48	0.008	0.007	0.03	0.4	0.05	0.01	<0.01	0.0035
Typical Mn rutile filler metal	E71T-1C H4 [19]	0.045	0.51	1.26	0.009	0.012	0.03	0.01	0.01	<0.01	0.01	-
Low Mn rutile filler metal	E71T1-GM [19]	0.05	0.47	0.18	0.007	0.007	0.03	0.42	0.02	0.01	0.01	-

Table 3. Mechanical properties of the base and filler metals according to EN 10204 2.2 reception certificate

Designation		Rp0.2 (MPa)	Rm (MPa)	A% (%)	KV2 (J) (at T)
Base metal for mechanical properties assessment and base plate for hot cracking susceptibility determination	S355J2+N [16]	444	544	30	242 (-20°C)
Round bar	C35 [17]	407	637	23	-
Round bar	S355J2+AR [16]	377	540	34	229 (-20°C) 239 (-40°C)
Typical Mn metal-cored filler metal	E70C-6M H4 [18]	485	581	25	73 (-30°C) 104 (-20°C)
Low Mn metal-cored filler metal	E70C-6M H4 [18]	463	523	30	97 (-29°C)
Typical Mn flux-cored filler metal	E71T-1C H4 [19]	571	630	23	60 (-40°C) 81 (-30°C) 104 (-20°C)
Low Mn flux-cored filler metal	E71T1-GM [19]	434	502	28	91 (-29°C) 111 (-18°C)

2.2 Welding

2.2.1 Mechanical properties assessment

Welded joints were produced using a fully mechanised robotic system. Type 1.3 V-groove butt welds with permanent backing were fabricated in the flat position (ISO 6947-PA) in accordance with NF EN ISO 15792-1 [20] (Fig. 4).

Dimensions in millimetres

Type	t	a	b	u	β degree	l
1.0	12	≥80	10			
1.1	12	≥90	12			
1.2	16	≥100	14			
1.3	20 $^{+1,0}_{-1,0}$	≥125	16 $^{+1,0}_{-0}$	≥6	$10^{+2,5}_{-0}$	≥150
1.4	25	≥125	20			
1.5	30	≥200	25			
1.6	20	≥150	20			
1.7	25	≥150	24			

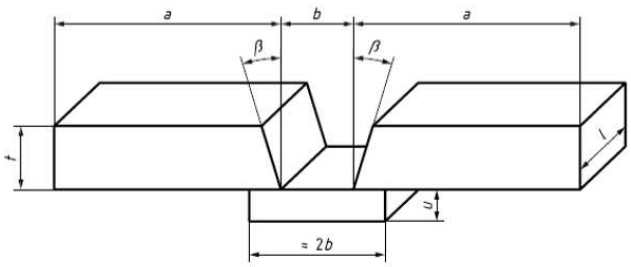


Fig. 4. Typical dimensions of the tests specimens for assessing mechanical properties in the fusion zone [20]

The welding parameters used for specimen preparation are summarised in Table 4.

Table 4. Summary of studied configurations for mechanical properties assessment

Configuration	Current (A)	Voltage (V)	Welding speed (cm/min)	Wire speed (m/min)	Heat input (kJ/mm)	Preheating and interpass temperature (°C)
Low Mn metal-cored filler metal	248	27	40	7.4	1.00	250
	333	30.8	24	11.6	2.56	250
Low Mn flux-cored filler metal	263	25.3	40	11.6	0.99	250
Typical Mn metal-cored filler metal	249	27	40	7.4	1.00	250
	310	30.7	23	11.5	2.48	250
Typical Mn flux-cored filler metal	260	25.2	40	11.6	0.98	250

2.2.2 Hot cracking susceptibility

For hot-cracking tests, the specimens were welded using a robotic system equipped with a two-axis positioner, allowing the round bar to be tilted at 45° and rotated to maintain a flat welding position (Fig. 5a).

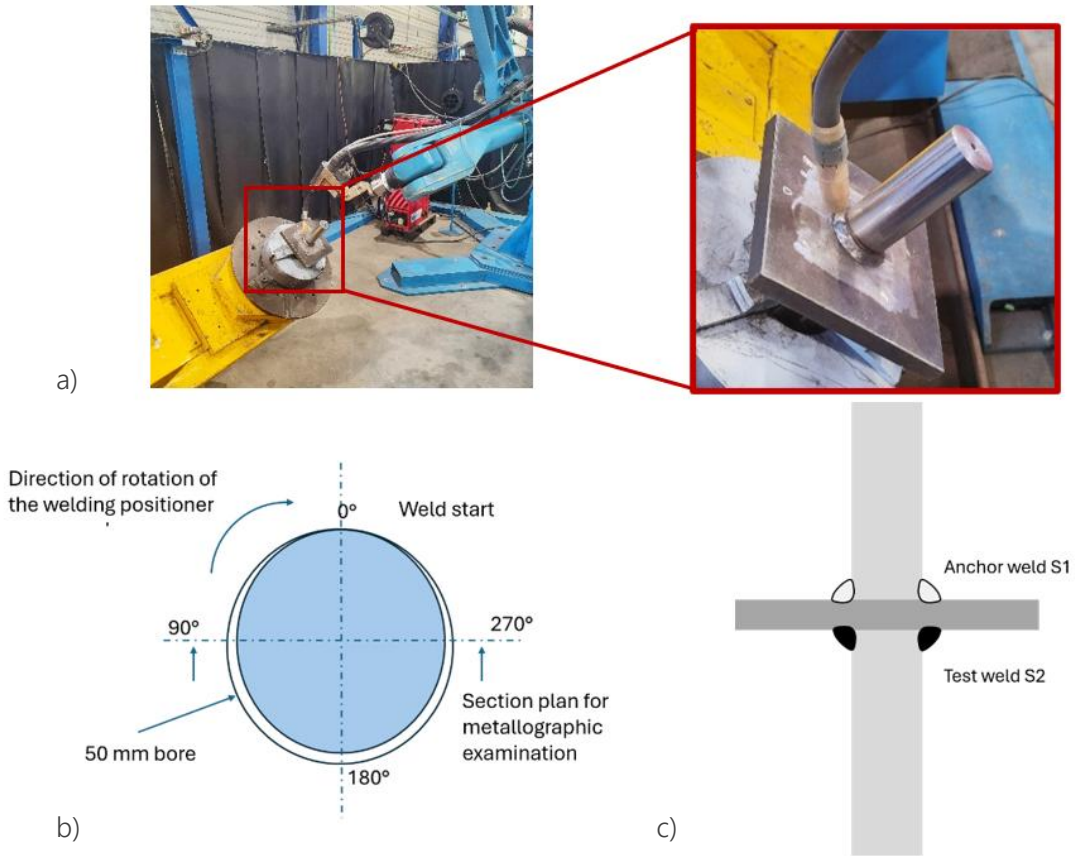


Fig. 5. a) photographs of the robotic system used, b) schematic diagram of the welding configuration and position of the future metallographic cut, c) schematic representation of the anchor weld and the test weld

The assemblies were first tack-welded using the TIG process in order to maintain a controlled gap between the round bar and the plate (Fig. 5b). Welding was then carried out in two stages. First, an anchor weld (S1) was deposited on the tacked side to ensure clamping all around the round bar. After complete cooling was completed, the test weld (S2) was produced with a linear heat input of 1.0 kJ/mm, on the other side of the assembly (Fig. 5c).

The configurations investigated are summarized in Table 5.

Table 5. Summary of studied configuration for hot cracking susceptibility

Round bar grade	Welding process	Filler metal	Mn content of filler metal according to EN 10204 3.1 reception certificate
C35	MAG welding with metal-cored electrode (138)	Low Mn metal-cored filler metal E70C-6M H4 [18]	0.48
C35	MAG welding with flux-cored electrode (136)	Low Mn flux-cored filler metal E71T1-GM [19]	0.17
C35	MAG welding with metal-cored electrode (138)	Typical Mn metal-cored filler metal E70C-6M H4 [18]	1.44
C35	MAG welding with flux-cored electrode (136)	Typical Mn flux-cored filler metal E71T-1C H4 [19]	1.28
S355 J2+N	MAG welding with metal-cored electrode (138)	Low Mn metal-cored filler metal E70C-6M H4 [18]	0.48
S355 J2+N	MAG welding with metal-cored electrode (138)	Typical Mn metal-cored filler metal E70C-6M H4 [18]	1.44

2.3 Experimental procedures

2.3.1 Mechanical weld testing

The metallurgical weldability was assessed by analysing transverse cross-sections of the welded joints. Specimens were prepared using standard metallographic procedures and etched with ferric chloride.

Vickers hardness mappings were then performed in the fusion zone using a 500 µm grid. In addition, the chemical composition of the covering passes, where dilution is minimal, was determined by optical emission spectroscopy.

Longitudinal tensile tests were conducted to evaluate the mechanical properties of the welded joints. For each configuration, three cylindrical specimens (10 mm diameter) were extracted at mid-thickness in the centre of the fusion zone.

Charpy V-notch impact tests were carried out in accordance with ISO 148-1. Specimens (10 × 10 × 55 mm) were taken from the fusion zone at mid-thickness. For each configuration, nine specimens were tested at three different temperatures.

2.3.2 Hot cracking susceptibility assessment

After welding, metallographic sections of the S2 weld were extracted along the 90°/270° axis in order to identify cracks and quantify dilution between the round bar and the plate (Fig. 6).

The analysis was performed both in the polished condition and after etching with 3% Nital. A test was considered unsuccessful if at least one crack was observed on the round bar side. Cracks located on the plate side or at the root were not taken into account.

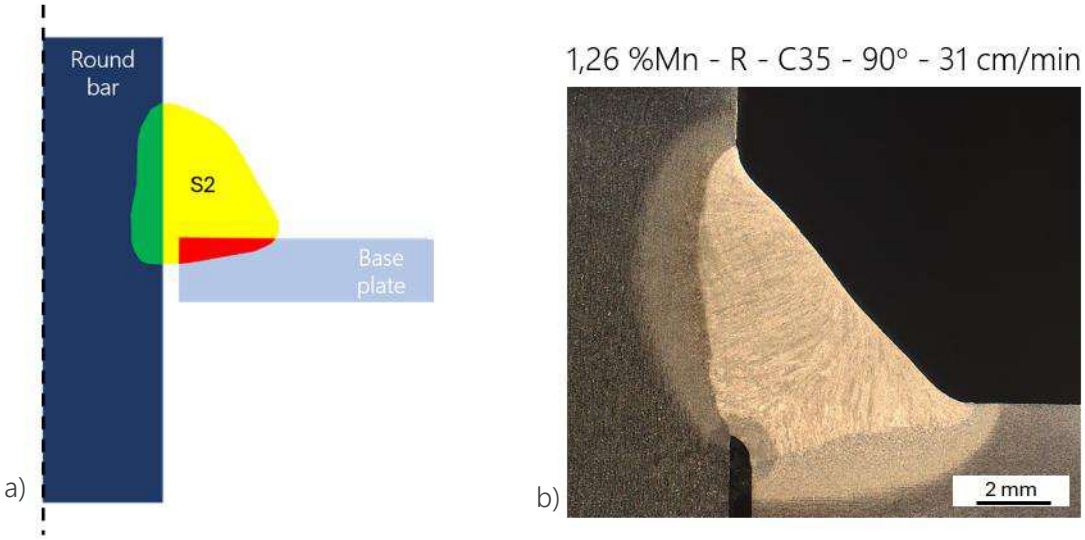


Fig. 6. a) schematic diagram of the process for determining the dilution ratio, with the dilution of the base plate shown in red and the dilution of the round bar shown in green – b) metallographic section of the test configuration 1,26 %Mn – Rutile-flux-cored - C35 - 90° - 31 cm/min

The chemical composition of the fusion zone was calculated by considering dilution into account, enabling the determination of the hot cracking susceptibility index 'UCS ' (Units of Crack Susceptibility), defined by [21] and adopted in the standard [22] as the 'USF' index (Unit of Susceptibility to Cracking). This index, expressed in arbitrary units and based on the mass percentage of the elements present in the molten pool, is defined by equation (1).

UCS/USF = 230 %C* + 190 %S + 75 %P + 45 %Nb – 12.3 %Si – 5.4 %Mn – 1 (where %C* = 0.08 if %C < 0.08 and %C* = %C if %C ≥ 0.08) (1)

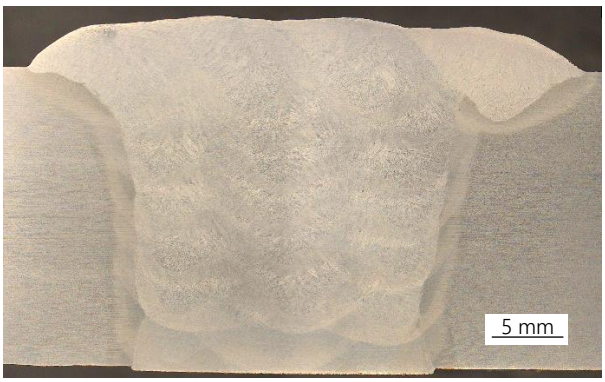
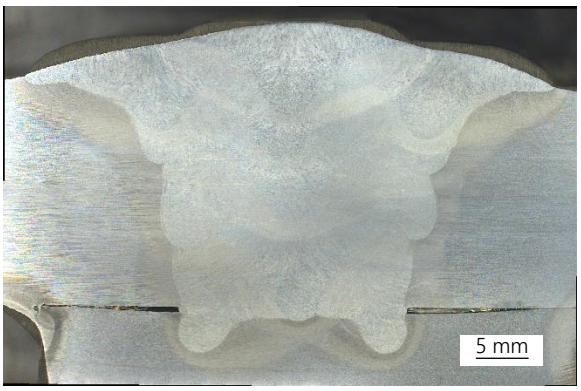
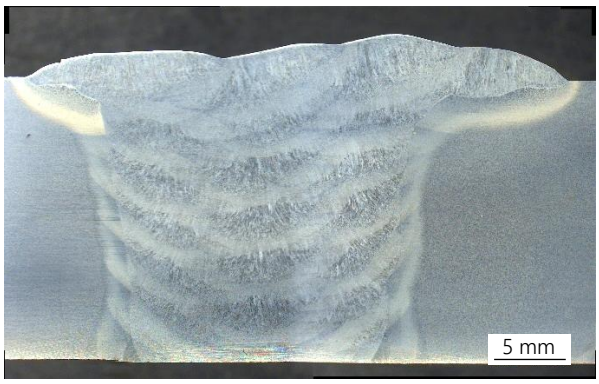
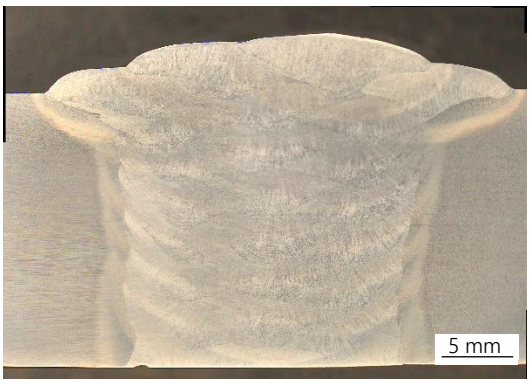
This formula, originally developed for submerged arc welded C and C-Mn steels assemblies, is now widely used to assess the risk of solidification cracking for other welding processes and other ferritic steels. However, it is valid only for the following molten metal compositions: %C: 0.03–0.23 %, %Mn: 0.45–1.6 %, %Si: 0.15–0.65 %, %Nb: 0–0.07 %, %S: 0.01–0.05 %, %P: 0.01–0.045 %, %Ni < 1 %, %Cr < 0.5 %, %Mo < 0.4 %, %V < 0.07 %, %Cu < 0.3 %, %Ti < 0.02 %; %Al < 0.03 %, %B < 0.002 %, %Pb < 0.01 % and Co < 0.03 %, which is the case here.

3 Results and discussion

3.1 Hardness

No welding defects (e.g. lack of fusion, inclusions or porosity) or metallurgical issues such as hot or cold cracking were detected during macrographic examination for any configuration (Table 6).

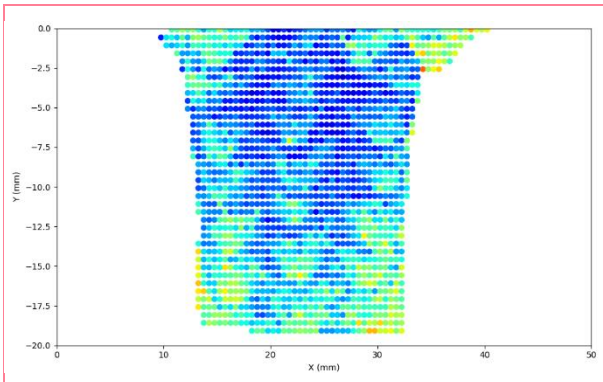
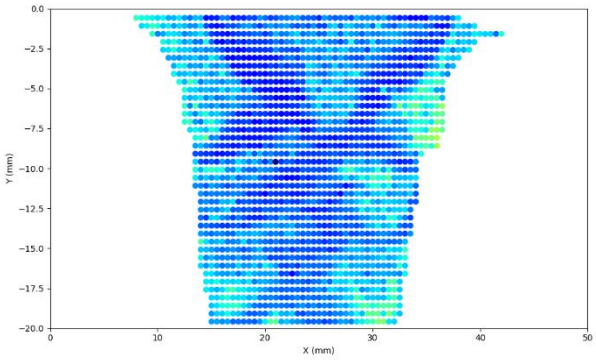
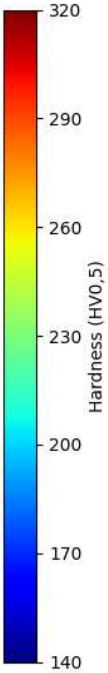
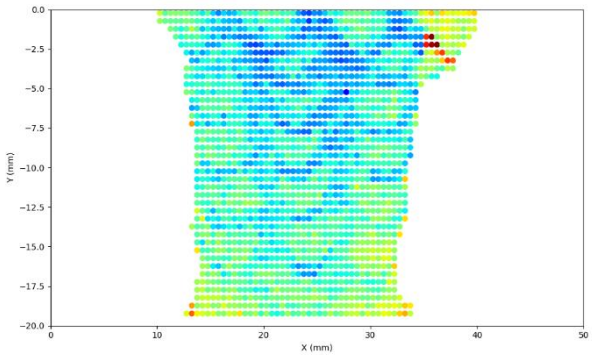
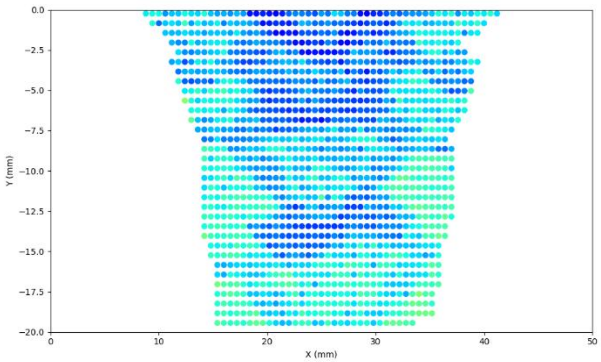
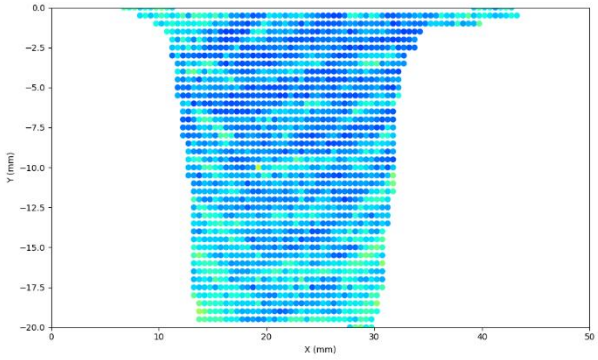
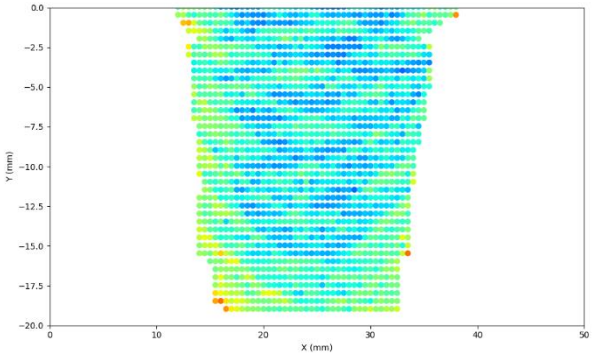
Table 6. Transverse macrographic view of each studied configuration

	
1.0 kJ/mm - Low Mn metal-cored filler metal	2.5 kJ/mm - Low Mn metal-cored filler metal
	
1.0 kJ/mm - Typical Mn metal-cored filler metal	2.5 kJ/mm - Typical Mn metal-cored filler metal
	
1.0 kJ/mm - Low Mn flux-cored filler metal	1.0 kJ/mm - Typical Mn metal-cored filler metal

Hardness mappings (Table 7) reveal that increasing the heat input results in a reduction in hardness within the fusion zone, due to enhanced tempering effects.

Furthermore, for a given heat input, a higher manganese content leads to increased hardness, reflecting the strengthening effect of manganese.

Table 7. Hardness mappings of the fusion zone of each studied configuration

		
1.0 kJ/mm - Low Mn metal-cored filler metal	2.5 kJ/mm - Low Mn metal-cored filler metal	
		
1.0 kJ/mm - Typical Mn metal-cored filler metal	2.5 kJ/mm - Typical Mn metal-cored filler metal	
		
1.0 kJ/mm – Low Mn flux-cored filler metal	1.0 kJ/mm - Typical Mn flux-cored filler metal	

3.2 Chemical composition

The chemical compositions measured in the covering passes are consistent with the corresponding EN 10204 certificates, confirming the limited dilution of the base material at this location (Table 8). As expected, the

manganese content ranges between 0.2% and 0.5% for low-manganese filler metals. This reduction is partially compensated by a higher nickel content compared with conventional consumables.

In some cases, increased heat input leads to a reduction in alloying element content (e.g. Cr, Ni and Cu), likely due to volatilisation during welding.

The higher content of carbon for the configuration Low Mn metal-cored 2.5 kJ/mm compared to 1 kJ/mm could be caused by the protection gas.

Table 8. Chemical composition (%wt) of the fusion zone of each configuration

Filler metal	Heat input (kJ/mm)	%C	%Si	%Mn	%S	%P	%Cr	%Ni	%Cu
Low Mn metal-cored	1.0	0.043 ± 0.003	0.46 ± 0.03	0.42 ± 0.03	0.008 ± 0.003	0.011 ± 0.003	0.03 ± 0.03	0.36 ± 0.03	0.04 ± 0.03
	2.5	0.051 ± 0.005	0.43 ± 0.03	0.45 ± 0.03	0.008 ± 0.003	0.011 ± 0.003	0.03 ± 0.03	0.33 ± 0.03	0.04 ± 0.03
Low Mn flux-cored	1.0	0.052 ± 0.005	0.47 ± 0.03	0.2 ± 0.03	0.008 ± 0.003	0.008 ± 0.003	<0.03	0.45 ± 0.03	<0.03
Typical Mn metal-cored	1.0	0.032 ± 0.003	0.71 ± 0.03	1.45 ± 0.05	0.022 ± 0.001	0.015 ± 0.001	0.029 ± 0.008	0.019 ± 0.007	0.028 ± 0.002
	2.5	0.035 ± 0.003	0.66 ± 0.05	1.41 ± 0.10	0.020 ± 0.003	0.017 ± 0.003	<0.03	<0.03	<0.03
Typical Mn flux-cored	1.0	0.031 ± 0.003	0.596 ± 0.03	1.32 ± 0.05	0.0043 ± 0.001	0.011 ± 0.001	0.03 ± 0.008	0.014 ± 0.007	0.014 ± 0.002

3.3 Tensile properties

All configurations satisfy the requirements of the relevant supply standards, meaning AWS specification for carbon steel electrodes for qas shielded arc welding [18] and flux cored arc welding [19] (Table 9). However, only the configuration involving a typical manganese metal-cored filler metal at high heat input meets the corresponding acceptance certificate values.

As presented on Fig. 7, increasing the heat input leads to a reduction in both yield strength and ultimate tensile strength, while slightly increasing elongation. Moreover, for a given heat input, low-manganese filler metals exhibit lower strength, but higher ductility compared with conventional consumables. This behaviour is consistent with the lower hardness values observed in the fusion zone.

Table 9. Mechanical characteristics of the weld zone of each configuration and comparison to values of EN 10204 2.2 acceptance certificates and supply standards meaning AWS specification for carbon steel electrodes for qas shielded arc welding [18] and flux cored arc welding [19] (in green, the results greater than the certificate, in blue, the results greater than the supply standard but lower than the certificate, in red, the results lower than the supply standard, between brackets, the minimum value imposed by the supply standard)

	Tensile properties	$R_{p0.2}$ (MPa)	R_m (MPa)	A% (%)
Metal-cored filler metal – Low Mn	*Certificate EN 10204 2.2 -1,6 kJ/mm [* [18]*]*	463 [400]	523 [480]	30 [22]
	Weld – 1 kJ/mm	454 ± 7	529 ± 6	26 ± 2
	Weld – 2.5 kJ/mm	432 ± 3	533 ± 3	28 ± 2
Flux-cored filler metal – Low Mn	*Certificate EN 10204 2.2 -1,4 kJ/mm [* [19]*]*	434 [400]	502 [480]	28 [22]
	Weld – 1 kJ/mm	459 ± 3	539 ± 1	25 ± 1
Metal-cored filler metal – Typical Mn	*Certificate EN 10204 2.2 – NA [* [18]*]*	485 [400]	581 [480]	25 [22]
	Weld – 1 kJ/mm	547 ± 8	606 ± 6	24 ± 1
	Weld – 2.5 kJ/mm	504 ± 3	585 ± 2	26 ± 0
Flux-cored filler metal – Typical Mn	*Certificate EN 10204 2.2 – NA [* [19]*]*	571 [400]	630 [480]	23 [22]
	Weld – 1 kJ/mm	565 ± 4	614 ± 4	23 ± 1

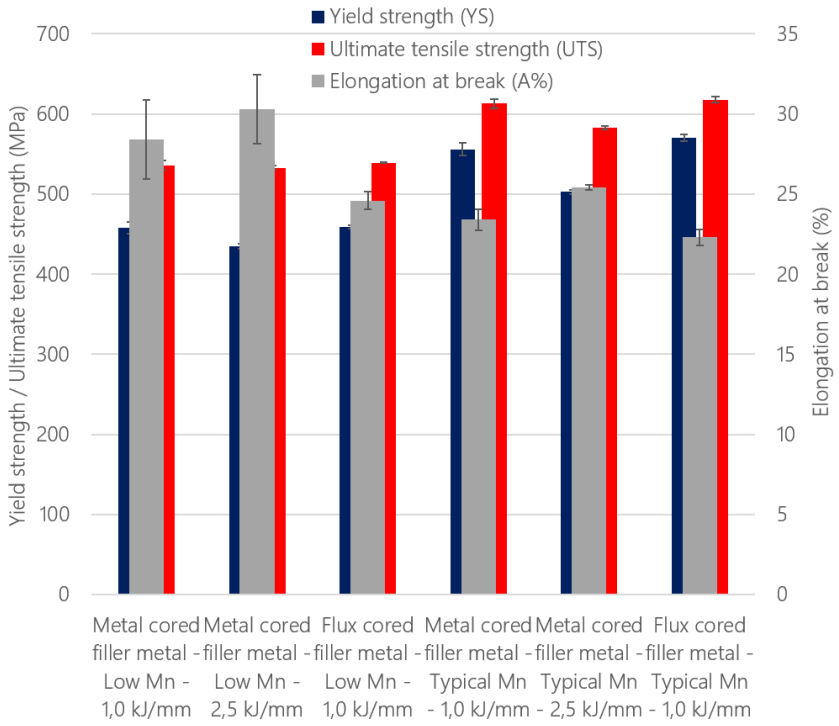


Fig. 7. Evolution of yield strength (in blue), ultimate tensile strength (in red) and elongation at break (in grey) depending on the studied configuration

3.4 Charpy-V impact test properties

With the exception of low-manganese flux-cored filler metals, all configurations meet the minimum absorbed energy requirements defined by the applicable standards (Table 10): :27J at -30°C for metal-cored filler metal and 27J at -40°C for flux-cored filler metal but not the certificate acceptance values.

However, only the configuration « low Mn – metal-cored filler metal » at 2.5 kJ/mm achieves the higher values reported in the acceptance certificates, suggesting that these values may be non-conservative.

Unlike the tensile properties, compared with conventional consumables, low-manganese metal-cored wires exhibit improved impact toughness, particularly at higher heat input. This behaviour may be attributed to their increased nickel content.

In contrast, the low-manganese flux-cored wire, which contains a particularly low manganese level (0,2 % of Mn vs 0,45 % for the low Mn metal-cored filler metal), exhibits significantly reduced toughness.

Table 10. Mean absorbed energy of the weld zone of each configuration and comparison to values of EN 10204 2.2 acceptance certificates and supply standards meaning AWS specification for carbon steel electrodes for qas shielded arc welding [18] and flux cored arc welding [19] (in green, the results greater than the certificate, in blue, the results greater than the supply standard but lower than the certificate, in red, the results lower than the supply standard, between brackets, the minimum value imposed by the supply standard)

	Mean absorbed energy at T	-30°C	-40°C	Temperature at which CVN = 28 J – Tk28 (°C)	50 % brittle fracture appearance Charpy impact transition temperature – T50 (°C)
Metal-cored filler metal – Low Mn	*Certificate EN 10204 2.2 -1,6 kJ/mm [[18]]*	*97 [27]*	-	-	-
	Weld – 1 kJ/mm	91	52	-48	-31
	Weld – 2.5 kJ/mm	100	64	-53	-35
Flux-cored filler metal – Low Mn	*Certificate EN 10204 2.2 -1,4 kJ/mm [[19]]*	*91*	*[27]*	-	-
	Weld – 1 kJ/mm	39	25	-45	-20
Metal-cored filler metal – Typical Mn	*Certificate EN 10204 2.2 – NA [[18]]*	*73 [27]*	-	-	-
	Weld – 1 kJ/mm	50	33	-45	-15
	Weld – 2.5 kJ/mm	31	18	-33	-6
Flux-cored filler metal – Typical Mn	*Certificate EN 10204 2.2 – NA [[19]]*	*81*	*60 [27]*	-	-
	Weld – 1 kJ/mm	62	45	-54	-21

3.5 Hot cracking susceptibility

The results obtained previously [14] are supplemented by the present study and shown in Fig. 8. Overall, depending on the UCS a systematic reduction in welding speed is necessary to avoid the risk of hot cracking.

Details for each grade are given in the following sections.

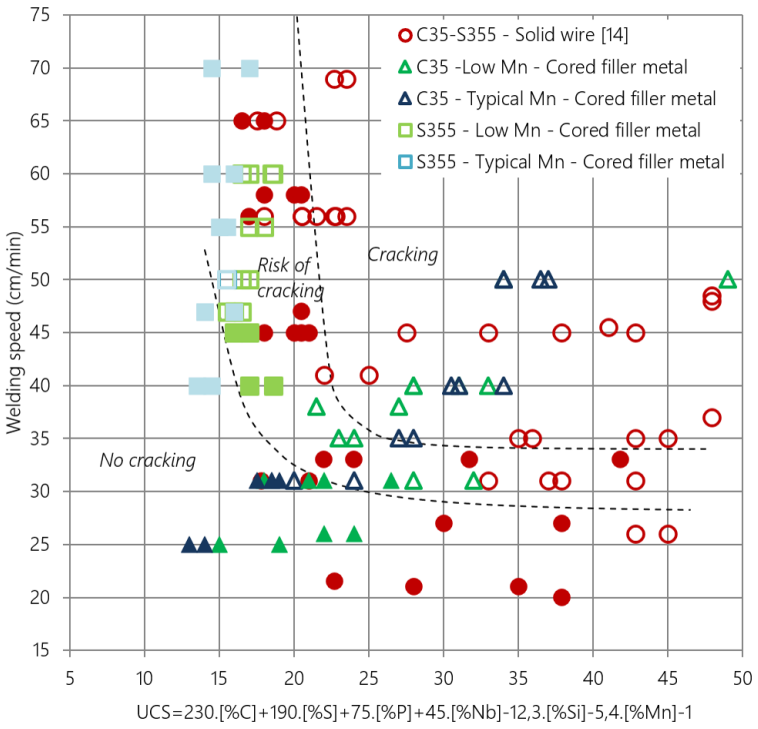


Fig. 8. Admissible welding speed regarding hot-cracking susceptibility depending on UCS index (filled symbol: no cracking, outline symbol: cracking)

3.5.1 C35 grade

The results of the tests conducted on the C35 round bar are presented as a function of welding speed and USF index in Fig. 9.

For the C35 grade, the critical welding speed ranges from 29 to 33 cm/min at a heat input of 1.0 kJ/mm. No significant influence of manganese content or filler metal type is observed.

These results are consistent with previous findings, namely 28 cm/min, for the same grade, using the MAG solid wire G2Si [23], which would now correspond to the designation G3Si1 [10], containing 1.27 % Mn and indicate that the chemical composition of the base material dominates hot-cracking behaviour through dilution effects.

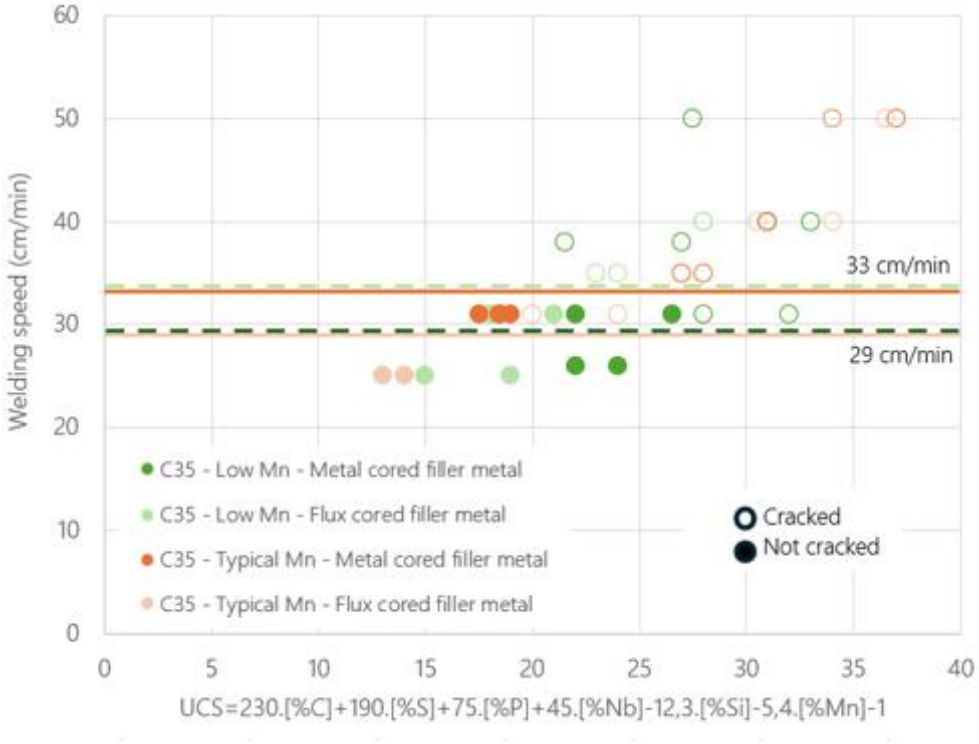


Fig. 9. Results of tests conducted on S355 grade, depending on the welding speed and UCS index

The standard NF EN 1011-2 [22] states that values below 10 USF indicate high resistance to hot cracking, whilst values above 30 indicate low resistance. For fillet welds with a depth-to-width ratio of approximately 1, the risk of cracking is confirmed from a value of 20 upwards. By limiting the depth-to-width ratio to 0.8, the permissible USF can be increased by approximately 9 units.

In the present work, all 37 specimens had a depth-to-width ratio of 0.8 or less. It was observed that below 19 USF, resistance to hot cracking is high (no cracks observed), whilst the risk is significant (cracks observed systematically) from 27 USF onwards (Fig. 10). This limitation does not entirely correspond to the zones defined in [22]: the beneficial effect of the depth-to-width ratio is not identified here. Nevertheless, cracks mainly appear at the periphery of the fusion zone (Fig. 11) and not at the center of the weld bead, possibly due to the dilution. Consequently, the geometry of the weld bead may have a lesser influence.

In terms of operational weldability, low-manganese flux-cored wire has a narrower operating range (wire speed) than standard wire and requires, for example, adjustments to the arc height to minimise spatter when used at low wire speeds such as 6.5 m/min.

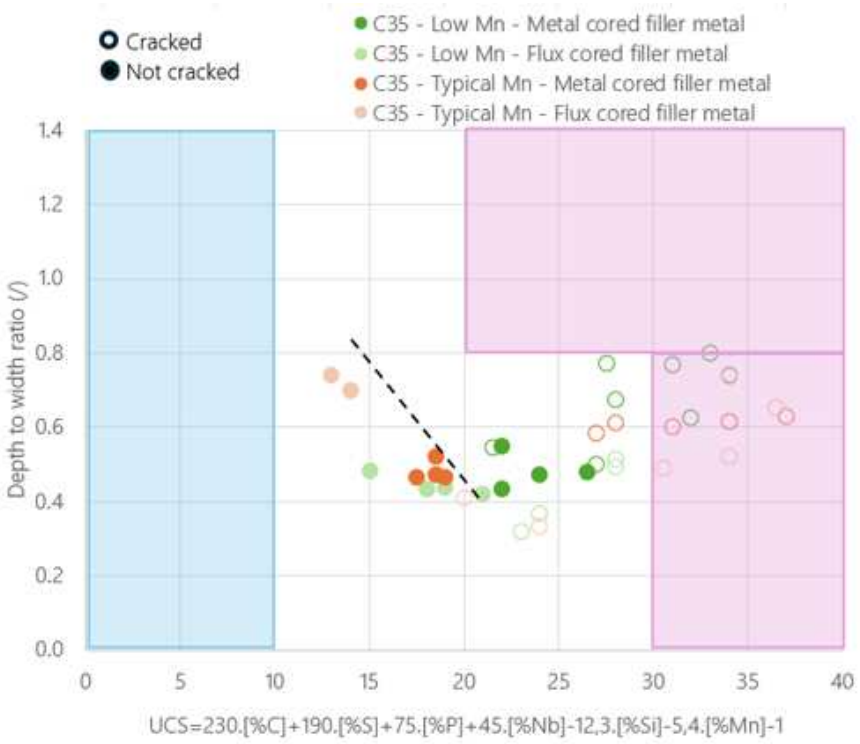


Fig. 10 . Crack sensitivity index and depth-to-width ratio of welds for S35 round bar (in blue, the zone defined by [22] as having high resistance to hot cracking; in pink, the zones defined by NF EN ISO 1011-2 as being at risk of hot cracking)

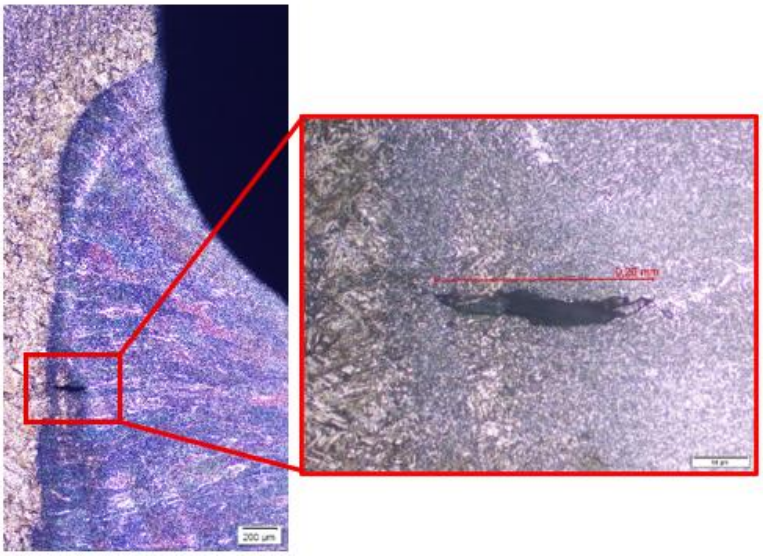


Fig. 11. Metallographic observation of the crack on 1,26 % Mn – Rutile flux-cored – C35 – 31 cm/min –270° Cut

3.5.2 S355 grade

The results of the tests conducted on the S355 round bar are presented as a function of welding speed and the USF index in Fig. 12. Only metal-cored wire was investigated here, and a clear influence of manganese content is observed. The critical welding speed is reduced to approximately 46 cm/min when using low-manganese wire.

In contrast, no cracking was observed with conventional wires within the investigated range, indicating improved resistance to hot cracking. The tests conducted did not result in cracking the joint, except at 50 cm/min, but on the side of the test plate. However, tests conducted at higher speeds failed to reproduce the defect, so it was not considered. As the generator's limit had been reached (400 A), it was not possible to investigate speeds higher than 70 cm/min to respect the heat input of 1.0 kJ/cm.

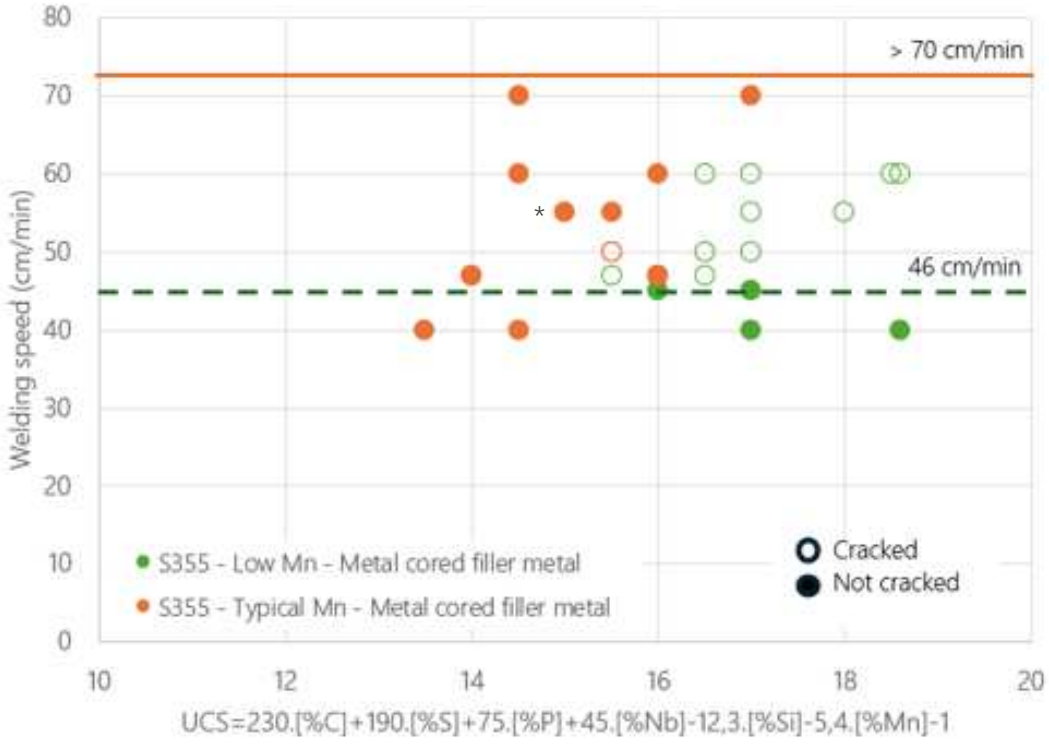


Fig. 12. Results of tests conducted on S355 grade, depending on the welding speed and UCS index (*: cracking on base plate)

The following comparisons can be made:

- Metal-cored wire with low Mn content versus solid G2Si wire [23]/G3Si1 [10], containing 1.27 % Mn and used by [14] : using the same grade of base metal, the MAG process and a linear heat input of 1 kJ/mm, the critical speeds obtained (46 cm/min and 50 cm/min respectively) and therefore the applications are similar,

- Metal-cored wire with low Mn content vs metal-cored wire with standard Mn content: with an S355 base metal, the use of the low-Mn wire becomes a limiting factor in automated or robotic welding, where welding speeds exceed 45 cm/min.

In this study, most tests had a depth-to-width ratio between 0.6 and 1.2. It was observed that, below 15 USF, resistance to hot cracking was high (no cracks observed). Systematic cracking (a proven risk) was not observed, whilst a USF of 18.5 was reached (Fig. 13). As with the C35 grade, this limitation does not entirely correspond to the zones defined in the NF EN ISO 1011-2 standard: the beneficial effect of the depth-to-width ratio is not

always verified here. Nevertheless, as with C35, cracks mainly appear at the periphery of the molten zone and not at the center of the weld bead. Consequently, the geometry of the weld bead may have a lesser influence.

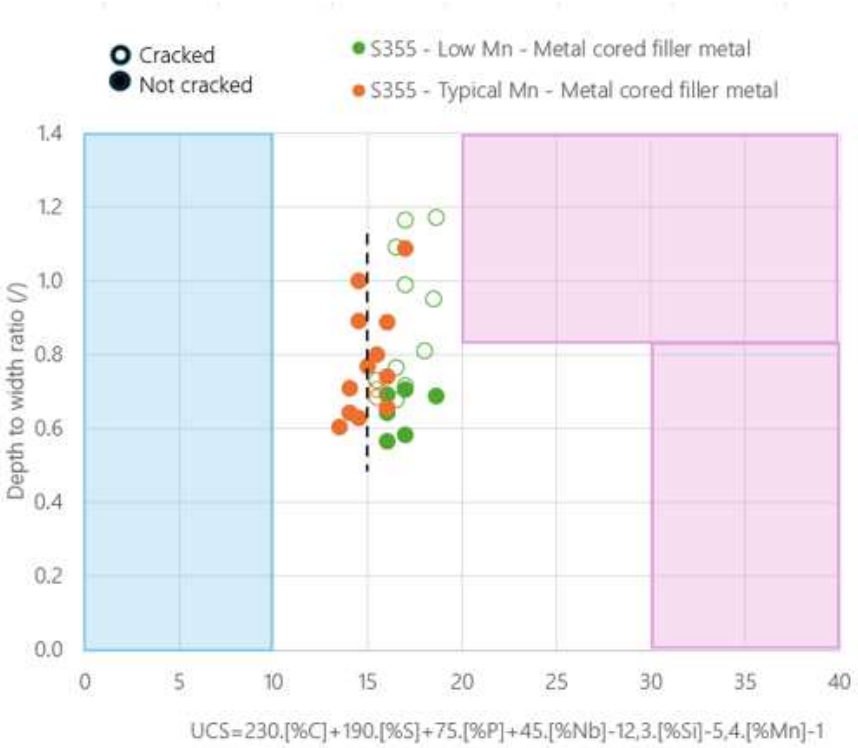


Fig. 13. Crack sensitivity index and depth-to-width ratio of welds for S355 round bar (in blue, the zone defined by [22] as having high resistance to hot cracking; in pink, the zones defined by NF EN ISO 1011-2 as being at risk of hot cracking)

4 Conclusion

This study investigated the weldability of low-manganese filler metals by examining different joint configurations, filler metal types (flux-cored and metal-cored), heat inputs (1 and 2.5 kJ/mm), and manganese contents (low: 0.2–0.5%; typical: approximately 1.2%). In addition, round-bar-through-plate tests were conducted to determine the critical welding speed associated with hot-cracking susceptibility at a heat input of 1 kJ/mm for C35 and S355 steels.

Overall, the results demonstrate that operational weldability remains satisfactory under the tested conditions and does not lead to unacceptable defects. However, some difficulties were observed with low-manganese flux-cored wires, particularly at high heat inputs or low wire feed speeds.

Although the addition of nickel enables compliance with standard requirements, tensile properties are consistently slightly lower than those obtained with conventional manganese filler metals. Furthermore, increasing the heat input systematically reduces yield strength and ultimate tensile strength, irrespective of the manganese content.

Regarding impact toughness, all metal-cored filler metal configurations satisfied the requirement of 27 J at −30 °C, whereas only the conventional flux-cored wires met the requirement at −40 °C. Low-manganese flux-cored wires therefore appear insufficient for applications requiring high toughness at low temperature.

With respect to hot-cracking susceptibility, no significant influence of manganese content was observed for C35 steel, where the fusion zone composition dominates cracking behaviour. In contrast, for S355 steel, the use of low-manganese metal-cored wire reduces the critical welding speed, thereby limiting its application in high-productivity welding processes.

In conclusion, the low-manganese filler metals investigated offer performance comparable to standard consumables in most cases. Nevertheless, limitations remain for specific applications, particularly when high toughness or high welding speeds are required. Further work should therefore consider a wider range of commercial products in order to generalise these findings.

Acknowledgement

Welding and testing were performed at the French Welding Institute, Yutz, France. The authors would like to acknowledge Alex Gutschmidt for his technical support in this work.

Author’s contribution

L. Guilmois: conceptualization, methodology, investigation, writing—original draft preparation, review and editing
S. Pigaux-Leys: investigation, project administration
L. Jubin: conceptualization, methodology, investigation, supervision, validation, writing—review and editing

Funding

This study received no external funding.

Data availability

Data used in the present study are available in the manuscript only. Extra data if required are available on request.

Conflict of interest

The authors have no competing interests to declare that are relevant to the content of this article.

5 References

[1] INRS, *Recommandation R 443 - Soudage à l'arc électrique et coupage - Prévention des risques professionnels,* 2009.

[2] International Agency for Research on Cancer Working Group on the Evaluation of the Carcinogenic Risks to Humans , *Welding, molybdenum trioxide, and indium tin oxide.,* International Agency for Research on Cancer, World Health Organization., 2018.

[3] AWS, *Fumes and Gases in the Welding Environment,* American Welding Society, 1979.

[4] K. Y. Kirichenko, A. I. Agoshkov, V. A. Drozd, A. V. Gridasov, A. S. Kholodov, S. P. Kobylyakov et K. S. Golokhvast, *Characterization of fume particles generated during arc welding with various covered electrodes,* Nature - Scientific report, 8(1), 17169, 2018.

[5] E. Quecke, B. Quemerais et Z. Hashisho, *Review of welding fume emission factor development, Annals of Work Exposures and Health,* 2023, pp. 675 - 693.

[6] Ministère du travail, *Arrêté du 27 septembre 2019 fixant des valeurs limites d'exposition professionnelle indicatives pour certains agents chimiques,* 2019.

[7] NF EN ISO 15011-4, *Hygiène et sécurité en soudage et techniques connexes - Méthode de laboratoire d'échantillonnage des fumées et des gaz - Partie 4 : fiches d'information sur les fumées,* AFNOR, 2018.

[8] NF EN ISO 15011-1, *Hygiène et sécurité en soudage et techniques connexes - Méthode de laboratoire d'échantillonnage des fumées et des gaz - Partie 1 : détermination du débit d'émission de fumée lors du soudage à l'arc et collecte des fumées pour analyse,* AFNOR, 2009.

[9] C. Gérardin, «Produits à basse émission de fumées - Evaluation des fourchettes opératoires sur les caractéristiques mécaniques - CETIM study n°052407 - Unpublished,» 2013.

[10] NF EN ISO 14341, *Produits consommables pour le soudage - Fils-électrodes et métaux d'apport déposés en soudage à l'arc sous protection gazeuse des aciers non alliés et à grains fins - Classification,* AFNOR, 2020.

[11] NF EN ISO 17632, *Produits consommables pour le soudage - Fils électrodes fourrés pour soudage à l'arc avec ou sans gaz de protection des aciers non alliés et des aciers à grains fins - Classification,* AFNOR, 2016.

[12] P. Bourges, L. Jubin et P. Bocquet, Prediction of mechanical properties of weld metal based on some metallurgical assumptions, H. Cerjak et K. Easterling, Éds., The Institute of Material, 1993, pp. 201-212.

[13] NF EN ISO 15614-1, *Descriptif et qualification d'un mode opératoire de soudage pour les matériaux métalliques - Épreuve de qualification d'un mode opératoire de soudage - Partie 1 : Soudage à l'arc et aux gaz des aciers et soudage à l'arc des nickels et alliages de nickel,* AFNOR, 2017.

[14] F. Maltrud et F. Decaestecker, «Etude de la fissuration à chaud des soudures d'angle monopasse de nuance GS2 - CETIM study n°172540 - Unpublished,» 1991.

[15] NF EN ISO 14175:2008, *Produits consommables pour le soudage - Gaz et mélanges gazeux pour le soudage par fusion et les techniques connexes,* AFNOR.

[16] NF EN 10025-2, *Produits laminés à chaud en aciers de construction - Partie 2 : conditions techniques de livraison pour les aciers de construction non allié,* AFNOR, 2019.

[17] NF EN ISO 683-1, *Aciers pour traitement thermique, aciers alliés et aciers pour décolletage — Partie 1 : Aciers non alliés pour trempe et revenu,* AFNOR, 2018.

[18] AWS A5.18/A5.18M:2021, *Specification for Carbon Steel Electrodes and Rods for Gas Shielded Arc Welding.*

[19] AWS A5.20/A5.20M:2005 (R2015), *Specification for Carbon Steel Electrodes for Flux Cored Arc Welding.*

[20] NF EN ISO 15792-1, *Produits consommables pour le soudage - Méthodes d'essai - Partie 1 : préparation des pièces d'essai et des éprouvettes de métal fondu hors dilution pour le soudage de l'acier, du nickel et des alliages de nickel,* AFNOR, 2020.

[21] N. Bailey et S. Jones, «The solidification cracking of ferritic steel during submerged arc welding,» *Welding Journal,* vol. 62, pp. 217s-231s, 1978.

[22] NF EN 1011-2, *Soudage - Recommandations pour le soudage des matériaux métalliques - Partie 2 : Soudage à l'arc des aciers ferritiques,* AFNOR, 2002.

[23] NF A81-311, *Fils électrodes métalliques nus massifs pour soudage à l'arc sous gaz de protection déposant un métal non allié ou faiblement allié - Symbolisation - Produits d'apport,* AFNOR, 1980.