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Influence of dilution on properties of high strength steel weld metals

Abstract: Chemical compositions of high strength steels and welding consumables differ significantly and dilution can therefore affect weld metal properties. Effects of dilution were studied by welding steels with yield strengths of 777 MPa and 1193 MPa using several arc welding methods with the addition of welding filler materials with a strength >800 MPa. Butt welds were produced in 12 mm plates and weld metal cooling rates were documented. High quality welds were produced efficiently with all welding methods and dilution varied between 3% for manual metal arc welding to 73% for laser-hybrid welding. Weld metals were martensitic/bainitic with proportions of microstructural constituents depending on alloying content and cooling rate. Overmatching weld metal strength was achieved for all welds in Weldox 700, and strengths >1000 MPa were recorded for Weldox 1100. Fracture in transverse tensile testing was for both steels located in the base material or HAZ. Low dilution, rapid cooling and single pass welding contributed to higher strength. Impact toughness decreased with increasing strength and increasing dilution. In conclusion, many welding methods can be used successfully for welding of high strength steels but effects of dilution and cooling rate should be considered when optimising properties.

Keywords: high strength steels, dillution, Weldox steel, welding properties

Introduction

The demand for high strength steels with yields strengths of 700 MPa and above is continuously increasing. Typical applications include offshore structures, cranes and pipelines. Such applications require a range of welding processes, offering flexibility and productivity, to make high strength steels practical and competitive. Steels with yield strengths up to at least 900 MPa have for many years been successfully welded, in many cases with matching strength weld metals. There is however a growing demand for welding of even higher strength steel

producing welds with matching strength. As a consequence there is also a need for improved higher strength welding consumables and a better knowledge of how variations in welding, including choice of welding method and parameters such as heat input and interpass temperature, affect weld properties [1-9].

Modern high strength steels are lean in composition and achieve their strength via optimised and well controlled combinations of rolling, cooling and tempering operations during production. This has the advantages of keeping alloying costs at a minimum and

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allowing the production of steels with a range of strength levels with similar steel compositions. It also makes the steel less susceptible to hydrogen induced cold cracking as less hard structures form in the heat affected zone on cooling as the carbon content and the carbon-equivalents are kept at a reasonably low level. High strength welding consumables must however be more highly alloyed to produce a matching strength in the as-welded condition [3-8, 10]. The chemical composition of welding consumables and steels therefore differs significantly for higher strength levels and the difference increases as strength goes up. One consequence is that the degree of mixing of steel and add-

welding were used with the addition of commercially available and experimental welding filler materials with nominal strength levels above 800 MPa.

Experimental

Steels and welding consumables

Two high strength steels were selected for the studies. The steels are as shown in Table 1, lean in composition and achieve their strength through a precisely controlled production process including quenching and tempering. Plate material of 12 mm thickness with yield strengths of 777 MPa and 1193 MPa (Table 2) were used.

Table 1. Chemical composition and carbon equivalent of high strength steels (wt%).

Steel	Element															Pcm*
	C	Si	Mn	P	S	Cr	Ni	Mo	V	Nb	Cu	Al	Ti	B	N	
Weldox 700	.144	.27	1.11	.011	<.0005	.28	.051	.16	.012	<.005	.009	.045	.008	.0010	.002	.24
Weldox 1100	.169	.21	1,21	.008	<.0005	.19	.044	.61	.038	.014	.008	.051	.003	.0009	.003	.30

*Pcm = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 +V/10 + 5B (wt%)

ed filler material during welding (dilution) can have a strong effect on weld metal properties. Another factor that will influence weld properties is the cooling rate [11-12]. In practical welding there is always a need to consider both productivity aspects and ensuring sufficient strength and toughness in the weld metal and heat affected zone. This is often a challenge as increasing productivity can result in reduction in good properties of the base material heat affected zone and/or the weld metal.

The thrust of the present study was twofold. The first aim was to map how dilution of filler material with fused base material will affect mechanical properties of welds in steels with yield strengths of 777 MPa (Weldox 700) and 1193 MPa (Weldox 1100). The second aim was to see to what extent weld strength would match base material strength depending on choice of welding method and welding consumables. Several arc welding methods including laser-hybrid

Table 2 . Steel mechanical properties.

Steel	$Rp_{0.2}$ (MPa)	Rm (MPa)	A_5 (%)	Impact toughness at -40°C (J)
Weldox 700	777	833	17	184
Weldox 1100	1193	1389	11	49

Welding was done with addition of commercial and experimental welding filler materials with compositions as presented in Table 3. It can be seen that welding consumables have a lower C-content but are generally higher alloyed in Cr, Ni and Mo compared to the steels. Selection was based on availability and the aim to match steel strength when possible. In addition, both cored wires and solid wires were used for gas metal arc welding for comparison purposes. Typical properties of undiluted all-weld metals are presented in Table 4. Yield strength levels vary between 810 and 1006 MPa suggesting a matching strength when welding

Table 3 . Chemical composition and carbon equivalent of all-weld metals (wt%).

Consumables	Element															Pcm*
	C	Si	Mn	P	S	Cr	Ni	Mo	V	Nb	Cu	Al	Ti	B	N	
Covered electrodes for MMA welding																
OK 75.78	.053	.33	2.2	.008	.005	.51	3.30	.62	.016	.009	.009	.004	.013	<.0002	.01	.30
OK 73.15	.11	.44	.98	.008	.002	0.63	3.30	.85	.003	.006	.017	.003	.023	<.0002	.007	.32
Solid wires for GMAW																
OK Aristorod 79	.087	.57	1.55	.010	.007	0.28	1.86	.43	.003	.004	.031	.003	.002	.0008	.016	.26
OK Aristorod 89	.082	.70	1.60	.004	.004	0.39	2.24	.55	.006	.005	.034	.006	.021	.0007	.011	.28
Metal cored wires for GMAW																
Coreweld 89	.09	.51	1.33	.010	.012	.51	2.71	.69	.002	.005	.023	.005	.007	.0003	.004	.29
H184	.10	.54	1.26	.010	.008	.55	2.62	.71	.003	.004	.028	.010	.012	.0002	.005	.30
Flux/ metal cored wires combinations for SAW																
OK Flux 10.63/ DA090	.089	.38	1.60	.011	.005	.04	2.50	.98	.003	.006	.054	.020	.011	.0002	.003	.29
OK Flux 10.63/ DA091	.11	.39	1.70	.011	.005	.04	2.59	1.05	.003	.007	.036	.021	.010	.0002	.003	.33

*Pcm = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 +V/10 + 5B (wt%)

the lower strength steel and undermatching for the stronger steel grade.

Welding

Conventional arc welding methods including manual metal arc (MMA), gas metal arc welding (GMAW), rapid arc (RA) welding and submerged arc welding (SAW) were used as well as laser-gas metal arc hybrid welding (Laser-Hybrid). RA welding is a high speed short-arc variant of GMAW. It uses higher wire speed, a longer electrode stick out and lower voltage than traditional GMAW techniques and permits welding speed and productivity to be increased significantly.

Joint angles and shielding gases were selected as appropriate for each welding method and are detailed in Table 5. Welding was done against a backing plate of the same steel grade with the exception of Laser-Hybrid welding. Preheating to 50°C and 75°C was used for welds in Weldox 700 and Weldox 1100, respectively.

The cooling rate is well known to be a significant factor in determining the properties of welds in high strength steels. Welding procedures were therefore adapted with the aim of ensuring comparable cooling rates as measured

Table 4 . All-weld metal mechanical properties.

Consumables	$R_{p0.2}$ (MPa)	R_m (MPa)	A_5 (%)	Impact toughness at -40°C (J)
OK 75.78	956	1058	15	55
OK 73.15	996	1128	15	74
OK Aristorod 79	810	900	18	55
OK Aristorod 89	920	1000	18	60
Coreweld 89	931	993	19	82
H184	992	1046	15	78
OK Flux 10.63/ DA090	961	1012	19	75
OK Flux 10.63/ DA091	1006	1063	16	74

by insertion of thermocouples into the weld pool. Table 5 gives the resulting number of weld beads for each weld.

Mechanical testing

The strength was measured along the weld and transverse to the weld whereas impact toughness was only tested at the weld centre. Tensile specimens were machined longitudinally from the weld joint centres with a specimen gauge diameter of 7 mm. Specimens for transverse

Table 5. Welding details.

Welding method & type of welding consumable	MMA	GMAW				SAW, cored wire
		solid wire	cored wire	Rapid Arc, solid wire	GMAW Laser-Hybrid, solid wire	
Weldox 700						
Welding consumable	OK 75.78	OK Aristorod 79	Coreweld 89	OK Aristorod 79	OK Aristorod 79	OK Flux 10.63/ DA090
Shielding gas	-	Ar+8%CO_2	Ar+18%CO_2	Ar+8%CO_2	Ar+8%CO_2	-
Joint angle	60°V			15°V	7°V	60°V
Beads	10	7	7	1	1	8
Weldox 1100						
Welding consumable	OK 73.15	OK Aristorod 89	H184	OK Aristorod 89	OK Aristorod 89	OK Flux 10.63/DA091
Shielding gas	-	Ar+8%CO_2	Ar+18%CO_2	Ar+8%CO_2	Ar+8%CO_2	-
Joint angle	60°V			15°V	7°V	60°V
Beads	10	7	7	1	1	8

tensile testing had a width of 25 mm. The thickness was between 10 and 12 mm as the amount of material that had to be removed to assure specimens were flat varied.

For Charpy-V testing, transverse specimens were machined having a cross section of 10 by 10 mm, notched perpendicular to the welding direction in the weld metal centre. Impact values were recorded for temperatures from -80°C up to room temperature testing 5 specimens at each temperature.

Hardness testing was performed on cross sections perpendicular to the welding direction using Vickers method with a 10 kg load (HV10) 2 mm from the top and bottom plate surfaces.

Chemical analysis

Chemical analysis was done at the centre of cross-sections of welds except for Laser-Hybrid welds where analysis was performed on the top. The elemental concentrations were determined with optical emission spectroscopy, except for C, S, O and N where combustion analysis was applied. The weld metal, all-weld metal and base material compositions were used to calculate dilution levels.

Microstructural characterisation

Microstructures were studied by light optical and scanning electron microscopy. Cross-sections of the welds were extracted perpendicular to the welding direction. Samples were mounted in bakelite, wet ground, polished and etched using 2% nital. Identification of microstructural constituents was done based on SEM micrographs in reference [13].

Table 6. Number of beads and cooling time between 800°C and 500°C.

Weld	MMA	GMAW/solid wire	GMAW/cored wire	GMAW/rapid arc	Laser-Hybrid	SAW
Weldox 700						
Cooling time $t_{8/5}$ (s)	5	6	8	12	5	10
Number of beads	10	7	7	1	1	8
Weldox 1100						
Cooling time $t_{8/5}$ (s)	5	7	8	12	5	10
Number of beads	10	7	7	1	1	8

Results

Welding

High quality, defect free welds could be produced efficiently with all welding methods after some fine tuning of welding procedures. Examples of cross sections for welds in Weldox 1100 are shown in Figure 1 illustrating the large variation in the number of beads and weld widths used to vary dilution over a wide range. An unintentional consequence of this was that it was not possible to keep cooling rates constant. The measured cooling times between 800°C and 500°C therefore varied between 5s for MMA and Laser-Hybrid welds to 10 s with SAW and 12 s with rapid arc welding (Table 6).
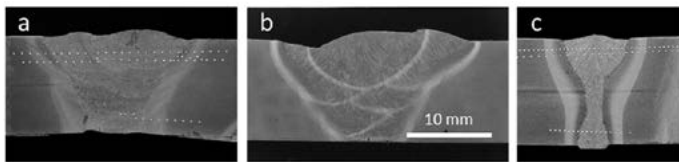
Fig. 1. Cross sections of a) MMA weld with 10 beads, b) GMAW weld with solid wire using 7 beads and c) single pass Laser-Hybrid weld in Weldox 1100. Hardness indentations can be seen in a) and c)

Weld metal microstructure

The last bead weld metal microstructures were mixtures of martensite and bainite (Figure 2). Martensite became more predominant as strength increased with a higher alloying content and with more rapid cooling. Bainite was more common in the lower strength, lower alloyed and more slowly cooled welds. Mainly,
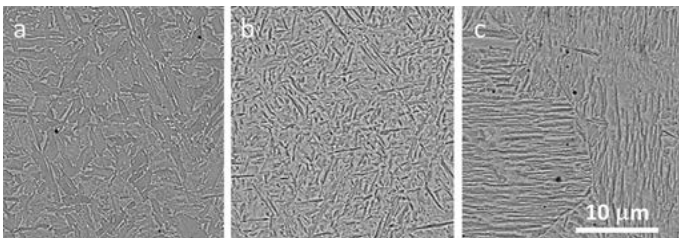

Fig. 2. SEM images of last bead weld metal microstructures all showing mixtures of martensite and bainite. a) The rapid arc weld in Weldox 700 has much upper bainite, b) the MMA weld in Weldox 700 is mainly a fine mixture of lower bainite and martensite and c) the SAW weld in Weldox 1100 shows a significant amount of martensite.

lower bainite was seen but some upper bainite appeared in particular in the relatively slowly cooled rapid arc welds.

Chemical analysis and dilution

Weld metal chemical compositions are presented in Table 7 together with calculated Pcm carbon equivalents and dilution levels. It is immediately evident from compositions that dilution is larger in single pass welds than in multipass welds. Calculating dilution is in principle straightforward provided compositions of base material, undiluted weld metal and weld metal are known. In practice, it is necessary to decide which element or elements to use for calculations. The reasons are that the level of alloying, the difference between steel, consumable and weld metal and the tendency of an element to be incorporated into slag or be oxidised in the arc will very much affect accuracy of dilution estimates. For example calculation of dilution in the GMAW/cored wire weld in Weldox 700 resulted in variations between -13% for Si to 37% for C. Eventually, Ni was selected for dilution calculations as this was the element for which the alloying level differed most between steel and consumables and as it is known to be relatively unaffected by desoxidation reactions and losses in the arc. As can be seen in Table 7 dilution varied between 3% for the 10 bead MMA weld in Weldox 700 to 73% for the Laser-Hybrid weld in the same steel.

Mechanical properties

Weld metal longitudinal strength was, as expected, on a higher level in the higher strength steel with yield strengths of 913 to 1057 MPa as compared to 790 to 1007 MPa in the lower strength steel (Table 8). The same was true for the transverse tensile strength ranging from 815 to 839 MPa in the Weldox 700 welds and from 1056 to 1142 MPa in Weldox 1100. It should be noted that fracture in all cases took place in the base material although generally closer to the fusion boundary in the stronger steel.

Table 7. Weld chemical compositions, carbon equivalents and dilution levels calculated from Ni-contents (wt%).

Weld	C	Si	Mn	P	S	Cr	Ni	Mo	V	Nb	Cu	Al	Ti	B	N	Pcm*	Dilu-tion (%)
							Element										
Weldox 700																	
MMA	.067	.39	2.25	.008	.004	.49	3.2	.59	.016	.011	.008	.005	.016	.0001	.014	0.31	3
GMAW/ solid wire	.10	.52	1.45	.011	.007	.29	1.46	.37	.004	.003	.02	.009	.003	.0011	.006	0.26	22
GMAW/ cored wire	.11	.54	1.31	.01	.009	.51	2.41	.62	.003	.005	.02	.008	.008	.0004	.002	0.30	11
GMAW/ rapid arc	.12	.48	1.46	.011	.004	.30	1.03	.32	.008	<.01	.021	.019	<.01	<.005	.004	0.29	46
Laser-Hybrid	.12	.37	1.26	.01	.002	.30	.54	.24	.01	.002	.02	.031	.007	.001	.008	0.24	73
SAW	.10	.34	1.42	.010	.006	.11	1.82	.79	.004	.004	.018	.025	.010	.0004	.003	0.27	28
Weldox 1100																	
MMA	.11	.39	1.04	.008	.002	.59	3.0	.81	.007	.009	.015	.006	.020	.0002	.012	0.31	9
GMAW/ solid wire	.093	.68	1.57	.004	.003	.38	2.0	.55	.010	.006	.030	.011	.024	.0007	.008	0.29	11
GMAW/ cored wire	.12	.59	1.35	.01	.007	.54	2.29	0.72	.009	<.01	.027	.019	.017	<.005	.004	0.35	13
GMAW/ rapid arc	.13	.56	1.53	.006	.002	.31	1.29	0.61	.023	.008	.023	.030	.025	<.005	.006	0.33	43
Laser-Hybrid	.15	.37	1.33	.006	.002	.26	.68	0.61	.03	.011	.020	.036	.014	.001	.009	0.30	71
SAW	.13	.33	1.48	.009	.006	.079	1.80	0.89	.012	.008	.018	.027	.007	.0004	.003	0.31	31

*Pcm = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 +V/10 + 5B (wt%)

Table 8. Weld metal mechanical properties.

Weld	Longitudinal tensile test			Transverse tensile test	Impact toughness	
	$R_{p0.2}$ (MPa)	R_m (MPa)	A_5 (%)	R_m (MPa)/fracture location	- 40°C (J)	+ 20°C (J)
Weldox 700						
MMA	1007	1050	16	825 / base material	61	89
GMAW / solid wire	812	965	12	834 / base material	73	116
GMAW / cored wire	832	990	16	813 / base material	64	104
GMAW / rapid arc	980	1112	14	833 / base material	75	130
Laser-Hybrid	790	982	14	815 / base material	18	69
SAW	885	963	16	839 / base material	73	102
Weldox 1100						
MMA	1057	1110	15	1115 /HAZ	72	88
GMAW / solid wire	932	1071	16	1056 /HAZ	34	89
GMAW / cored wire	958	1090	13	1075 /HAZ	31	64
GMAW / rapid arc	Lack of material			1100 /HAZ	47	no data
Laser-Hybrid	913	1152	10	1142 /HAZ	32	74
SAW	1001	1062	13	1071 /HAZ	41	67

Scatter was very small in impact toughness testing and typically only varied with a few Joules between the 5 samples tested at each temperature. Toughness at -40°C was with the exception of the Laser-Hybrid weld above 60 J for welds in the lower strength steel and above 30 J in the stronger steel.

Hardness was measured across the welds to identify location, width and depth of HAZ soft and hard zones and typical weld metal hardness levels. Hardness was as expected on a higher level in the higher strength steel and weld metals. Typically values for Weldox 700 were 250 HV10 in unaffected material, 200 HV10 in the soft zone in HAZ, maximum 350 HV10 in the hard zone in HAZ next to the fusion boundary and 250-350 HV10 in weld metal. Corresponding values for Weldox 1100 were 400 HV10 in unaffected base material, 280 HV10 in the soft zone in HAZ, maximum 380 HV10 in the hard zone in HAZ next to the fusion boundary and 300-400 HV10 in the weld metal. It can be noted that the maximum hardness in HAZ differed only 30 HV10 between the two steels.

Discussion

Welding and dilution aspects

Dilution levels were successfully varied over a large range from 3% to 73%. To achieve this cooling time, t8/5 had to be varied from 5 s to 12 s to produce sound welds. The number of weld beads also had to be varied from 1 to 10. Single pass welds are different from multipass welds in that the microstructure is used and tested as deposited without any tempering from subsequent weld passes. Such welds therefore typically have a higher strength and, at least for higher cooling rates, a lower toughness than multipass welds.

As the two steels and the welding consumables all have different compositions it was not feasible to directly relate weld metal mechanical properties to dilution as such. A convenient way when comparing the effect of composition on properties is however to rationalise the chemical composition into a single parameter. In the present study the Pcm carbon equivalent, (Pcm=C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+ +Mo/15+V/10+5B (wt.%)), originally developed for assessment of hydrogen cracking risk for low carbon structural steels, was used to permit direct comparison with literature data and to pool the data for the two steels.

Microstructures

The last bead weld metal microstructures were found to consist of mixtures of martensite and bainite (Figure 2). This is as shown in an earlier study on undiluted weld metal for one of the consumables used in this study [12], as expected, with proportions of martensite and bainite varying with cooling rate. Apart from martensite being the strongest and least tough microstructural constituent, one could also expect the "less fine" microstructures to be less tough. Defining a measure such as grain size describing the fineness is however a difficult task for these microstructures and was not attempted [14]. It was noted though that the slower cooled weld metals in some respect could be described as having a coarser structure which could contribute to lower impact toughness.

Strength

All welds in Weldox 700 were overmatching in strength (Tables 2 and 8), and cross weld testing in all cases took place in the base material. This is an important result as it shows that provided a suitable consumable is selected it is possible to achieve sufficient strength for a range of welding methods, cooling rates and dilution levels. The situation is different for the higher strength Weldox 1100 steel with yield and tensile strengths of 1193 MPa and 1389 MPa, respectively. Even though very impressive strength levels of up to 1057 MPa in yield and 1152 MPa in tensile strength were achieved, none of the welds matched the steel. It was noted though that cross weld tensile testing always resulted

in HAZ fracture suggesting that although the weld definitely is the weak link, it is not necessarily the weld metal as such that is weakest or have the lowest ductility. It should also be pointed out that the cross weld tensile strength varied between 1056 MPa and 1142 MPa and was thereby significantly stronger than in the less strong steel.

Previous studies [8, 15-17] have shown a nearly linear increase in weld metal tensile strength with Pcm and an increase but larger scatter for the yield strength. A plot of strength (Table 8) versus Pcm (Table 7) for the present weld metal results (Figure 3) do indeed show a trend of increasing strength with increasing Pcm although the scatter is significant. Another way of phrasing this is that a leaner weld composition resulting from a high dilution during welding is likely to result in a lower strength although other factors also need to be taken into account.
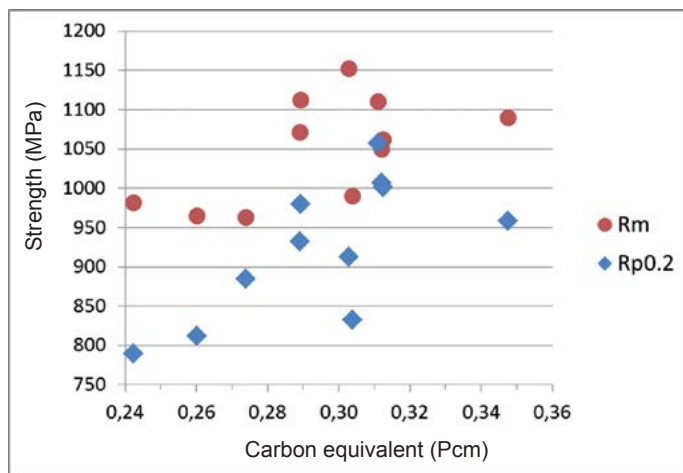
Fig. 3. Weld metal yield (Rp$_{0.2}$) and tensile strength (Rm) plotted as a function of the carbon equivalent Pcm.

A factor contributing to the scatter is most likely variations in cooling rate. It is well known that a higher cooling rate will promote formation of stronger microstructural constituents such as martensite as discussed in paragraph 3.2. An earlier study on undiluted weld metal for one of the consumables used in this study [11-12] showed for example that yield strength increased with about 110 MPa when decreasing t$_{8/5}$ with 7 s which is the range that cooling times varied within in this study. The data

points deviating most from a possible linear relationship, towards a lower than expected yield strength, are however the two GMAW welds with cored wire welded with an intermediate cooling rate. Obviously there are other factors than can be expressed by a simple compositional parameter and cooling time that explains the yield strength.

Two observations can be made looking in more detail at tensile strength data. Points deviating most from a possible linear relationship, towards higher strength, are those for welds with a high cooling rate and/or single pass welds. The effect of cooling rate is understandable in terms of effects on what microstructural constituents forms. The single pass effect is also understandable as no tempering will occur after deposition of the weld as is the case for all but the last bead in multipass welds. The full potential strength of the weld microstructure will therefore be used. This effect is very similar to the thinking behind formulation of high strength steels in that a lean composition can achieve a high strength if rapidly cooled.

Toughness

Impact toughness of welds is governed by several factors including weld metal cleanliness, oxygen content, type of inclusions, grain size and microstructural constituents [9, 18]. As strong microstructural constituents such as martensite are less tough than for example lean ferrite, it is expected and earlier reported [8] that impact toughness generally decreases with increasing strength. Figure 4 indeed showed a clear trend of decreasing impact toughness with increasing tensile strength. Scatter is small with the exception of the Laser-Hybrid weld in the Weldox 700 steel that showed unexpectedly low toughness. Further studies are needed to explain the behaviour of the Laser-Hybrid weld as chemical analysis and microstructural inspection did not provide any explanation. Although the trend is not very clear, there seem to be a tendency that lower dilution contributes

to better toughness. Comparing values from all-weld metal testing at -40°c with typical values for all consumables of 55-82 J, it is definitely so that dilution in most cases will lower impact toughness (Table 4). Again the single pass welds are confusing the pattern by having toughness values both above and below those expected. In conclusion it seems that toughness of high strength weld metals produced with state-of-the art welding consumables generally depend on the strength level and to a lesser extent on dilution. The toughness levels recorded are however with one exception on a level fulfilling common requirements.
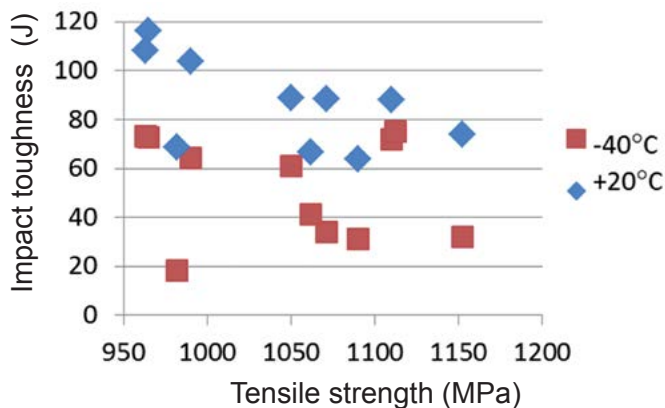
Fig. 4. Weld metal impact toughness plotted as a function of the carbon equivalent Pcm

Conclusions

The present study has mapped the influence of dilution on mechanical properties of welds in 777 MPa and 1193 MPa yield strength steels. Several arc welding methods were used with addition of welding filler materials with strength levels >800 MPa.

– Defect free welds were produced efficiently with all welding methods.
– Dilution varied between 3% and 73% with laser-hybrid welding resulting in the highest and mma in the lowest dilution.
– Weld metal microstructures were mixtures of martensite and bainite with martensite becoming more predominant with a higher alloying content and more rapid cooling.
– Weld metal strength was overmatching for all methods in the 777 MPa yield strength steel.

– Strength levels in the weld metal of up to 1057 MPa in yield and 1152 MPa in tensile was achieved in the stronger steel. However, fracture was in all cases located in the haz in transverse tensile testing.
– Low dilution and more rapid cooling resulted in the highest strength. Single pass welds were stronger than comparable multipass welds.
– Impact toughness of the weld metal decreased with increasing strength and increasing dilution. The negative effect of dilution was counteracted by a simultaneous decrease in strength.

Acknowledgements

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