# EFFICIENT WELDING OF HIGH STRENGTH STEEL

**Leif Karlsson, Lars-Erik Svensson and Kjell Hurtig**

*Department of Engineering Science, University West, SE-461 86 Trollhättan, Sweden*

leif.karlsson@hv.se

Abstract: Producing welds with properties matching those of the steel is a challenge at high strength levels. The present study investigated how cooling rates and dilution affects strength and toughness when welding steels with yield strengths of 777 MPa and 1193 MPa. Overmatching weld metal strength was achieved for the less strong steel and weld strengths >1000 MPa were recorded for the stronger steel. Fracture in transverse tensile testing was always located in base material or HAZ. Low dilution, rapid cooling and single pass welding contributed to higher strength. Impact toughness was higher for lower strength and low dilution.

Keywords: Welding, high strength steels, strength, toughness, dilution.

## 1. 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 since 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 (Svensson, 1999; Keehan, *et.al.*, 2006a-c; Svensson, 2007; Karlsson and Bhadeshia, 2011).

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. High strength welding consumables must however be more highly alloyed to produce a matching strength in the as-welded condition (De Meester, 2004 ;Keehan, *et.al.*, 2006a-c; Svensson, 2007). 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 added 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 (Karlsson, *et.al.*, 2004; Keehan, *et.al.*, 2010). 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 less good properties of the base material heat affected zone and/or the weld metal.

The thrust of the present study was twofold. First 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 welding were used with addition of commercially available and experimental welding filler materials with nominal strength levels above 800 MPa.

## 2. EXPERIMENTAL

### *2.1. 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%)

Table 2. Steel mechanical properties.

| **Steel** | **$R_{p0.2}$** (MPa) | **$R_m$** (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 the lower strength steel and undermatching for the stronger steel grade.

### *2.2. Welding and testing*

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.

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%)

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 |

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 aiming at ensuring comparable cooling rates as measured by insertion of thermocouples into the weld pool. Table 5 gives the resulting number of weld beads for each weld.

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 |

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

# 3. RESULTS

## *3.1. 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 5 s for MMA and Laser-Hybrid welds to 10 s with SAW and 12 s with rapid arc welding (Table 6).

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 |

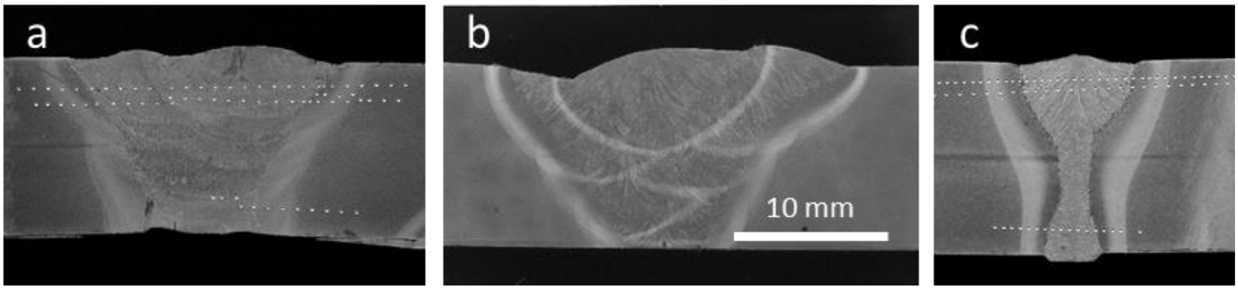

Fig. 1. Cross sections of a) MMA weld with 10 beads, b) GMAW weld with solid wire using 7 beads and c) single pass Laser-Hybrid weld in 12 mm Weldox 1100. Hardness indentations can be seen in a) and c).

## *3.2. Weld metal microstructure*

Last bead weld metal microstructures were mixtures of martensite and bainite. Martensite became more predominant as strength went up 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 lower bainite was seen but some upper bainite appeared in particular in the relatively slowly cooled rapid arc welds.

## *3.3. 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 single pass Laser-Hybrid weld in the same steel.

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

| **Weld** | **Element** | | | | | | | | | | | | | | | **Pcm*** | **Dilution (%)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **C** | **Si** | **Mn** | **P** | **S** | **Cr** | **Ni** | **Mo** | **V** | **Nb** | **Cu** | **Al** | **Ti** | **B** | **N** | | |
| | **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%)

### *3.4. 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.

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.

Table 8. Weld metal mechanical properties.

| | **Longitudinal tensile test** | | | **Transverse tensile test** | **Impact toughness** | |
|---|---|---|---|---|---|---|
| **Weld** | $R_{p0.2}$ (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 |

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 weld metal.

## 4. DISCUSSION

### *4.1. Welding and dilution aspects*

Dilution levels were successfully varied over a large range from 3% to 73%. To achieve this cooling times $t_{8/5}$ 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 higher strength and at least for higher cooling rates 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.

### *4.2. Microstructures*

The last bead weld metal microstructures were found to consist of mixtures of martensite and bainite. This is as shown in an earlier study on undiluted weld metal for one of the consumables used in this study (Keehan, *et al.*, 2010) 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. It was noted that the slower cooled weld metals in some respect could be described as having a coarser structure which could contribute to lower impact toughness.

### *4.3. Strength*

All welds in Weldox 700 were overmatching in strength (Tables 2 and 8) and cross weld testing in all cases took place in 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 (Svensson, 2007; Zhang and Farrar, 1997; Kang, *et al.*, 2000; Banguru, *et al.*, 2004) 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 2) 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.

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 (Karlsson, *et.al.*, 2004; Keehan, *et. al.*, 2010) showed for example that yield strength increased with about 110 MPa when

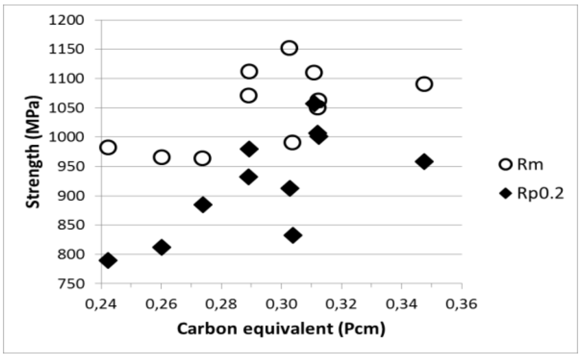

Fig. 2. Weld metal yield ($Rp_{0.2}$) and tensile strength (Rm) plotted as a function of the carbon equivalent Pcm.

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 that 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.

### *4.4. Toughness*

Impact toughness of welds is governed by several factors including weld metal cleanliness, oxygen content, type of inclusions, grain size and microstructural constituents (Karlsson and Bhadeshia, 2011). As strong microstructural constituents such as martensite is less tough than for example lean ferrite it is expected and earlier reported (Svensson, 2007) that impact toughness generally decrease with increasing strength. Figure 3 indeed show a clear trend of decreasing impact toughness with increasing tensile strength 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.

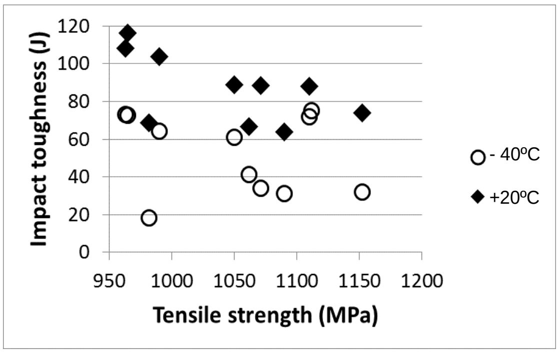

Fig. 3. Weld metal impact toughness plotted as a function of the tensile strength.

## 5. 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

The project was financially supported by The Knowledge Foundation (Sweden) and was performed in cooperation with SSAB AB, ESAB AB and AGA Gas AB. Company representatives (Helene Rasmuson and Markus Gustafsson, ESAB AB, Göteborg, Sweden, Anders R Ohlsson and Daniel Stemne, SSAB AB, Oxelösund and Borlänge, Sweden and Per Bengtsson, AGA Gas AB, Lidingö, Sweden) are thanked for their support, efforts and constructive comments during the project. Greger Wiklund (Luleå University of Technology, Sweden) is thanked for assistance with Laser-Hybrid welding. The skilful microscopy and hardness measurements by Dimosthenis Manitsas (University West, Sweden) is much appreciated.

## REFERENCES

Bangaru N. V., D. .P Fairchild, M. L. Macia, J. Y. Koo and A. Ozekcin (2004). Microstructural aspects of high strength pipeline girth welds. Proc. 4th Int. Pipeline Technology Conf., 9-13 May, Ostend, Belgium, pp. 798-808.

De Meester B. (2004), Trends in the development of steels and their weldability. Proc. Int. Conf. Advanced metallic materials and their joining. 25-27 Oct., Bratislava, Slovakia.

Kang B. Y., H. J. Kim and S. K. Hwang (2000). Effect of Mn and Ni on the variation of the microstructure and mechanical properties of low carbon weld metals. *ISIJ International*, **40,** pp. 1237-1245.

Karlsson L., E. Keehan, H.-O. Andrén, and H. K. D. H. Bhadeshia (2004). Development of high strength steel weld metals – potential of novel high-Ni compositions. *Proc. Eurojoin 5*, paper V6, 13-14 May, Vienna, Austria, EWA and SZA.

Karlsson L. and H.K.D.H. Bhadeshia (2011), Some European Developments in Welding Consumables. *Journal of the Japan Welding Society*, **80,** pp. 110-119.

Keehan E., L. Karlsson and H.-O. Andrén (2006a). Influence of C, Mn and Ni on strong steel weld metals: Part 1, effect of nickel. *Science and Technology of Welding and Joining*, **11**, pp. 1–8.

Keehan E., L. Karlsson, H.-O. Andrén, and H. K. D. H. Bhadeshia (2006b). Influence of C, Mn and Ni on strong steel weld metals: Part 2, increased impact toughness. *Science and Technology of Welding and Joining*, **11,** pp. 9–18.

Keehan E., L. Karlsson, H.-O. Andrén, and H. K. D. H. Bhadeshia (2006c). Influence of C, Mn and Ni on strong steel weld metals: Part 3, increased strength. *Science and Technology of Welding and Joining*, **11,** pp. 19-24.

Keehan E., J. Zachrisson, and L. Karlsson (2010). Influence of cooling rate on microstructure and properties of high strength steel weld metal. *Science and Technology of Welding and Joining*, **15,** pp. 233-238.

Svensson L.-E. (1999). Consumables for welding high strength steels. *Svetsaren*, **54**, pp. 29-33.

Svensson L.-E. (2007), Microstructure and Properties of High Strength Weld Metals. *Materials Science Forum*, **539-543**, pp. 3937-3942.

Zhang Z. and R. A. Farrar (1997). Influence of Mn and Ni on the microstructure and toughness of C-Mn-Ni weld metals. *Weld Journal*, **76**, pp. 183s - 196s.