# INFLUENCE OF CHEMICAL COMPOSITION OF WELD METAL ON THE PROPERTIES OF WELDED JOINT OF HIGH STRENGTH STEELS

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## ABSTRACT

The influences of composition of weld metal on its properties were investigated in this paper by using 700MPa grade steel and different welding materials with GMAW and SMAW. The GMAW wires produced two weld metals, one with medium amount alloying elements of Mn, Cr, Ni and Mo and the other one with higher Ni content and medium content of Mn, Cr and Mo as well, both producing weld metals with strength higher than the base metal. SMAW electrode produced less amount of elements thereof the strength of the weld metal is lower than the base metal. The weld metal with medium amount alloying elements has balanced strength, toughness and bending properties resulting in good comprehensive properties. The weld metal with high Ni content has higher toughness as expected, but its bending property is not qualified and some micro cracks originated during the bending test with some oxides of manganese and silicon found in/around the cracks by EPA analysis. SMAW weld metal with lower strength has good toughness but poor bending properties. It is likely that there is a strain concentration in the under-strengthened weld metal when bending test is ongoing. It is advisable that the chemistry of weld metal should be as close to that of base metal as possible and the strength of the weld metal properly over-strengthened.

## KEYWORDS

High strength steel welds composition properties

## INTRODUCTION

Modern advanced steel making technology has given birth to high strength steels one generation after another. The steels with tensile strength over 700MPa have been increasingly used in many important steel structures, which have resulted in many advantages such as a reduced structural weight, a reduced manufacturing cost and a high structural quality.

However, almost all these high strength steels have to be subject to welding procedure which may generate some problems, e.g. lower strength, poor toughness and cracking in the welded joint despite years of research in this area.

Factors placing influences on the properties of welded joints are the weld metal composition and the



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thermal cycle the welded joint has experienced. The weld metal is formed in such a way as the solidification starts from the wall of the weld melting pool, and grows in the direction of the maximum cooling gradient to form column branches from which then sub-branches form. The alloying elements tend to move to the solidification front, resulting in compositional differences between the locations that solidify at different times, so-called segregation. There will be obvious thermal cycle differences in multi-layer weld metal due to the heat effect of later welds on the former welds. Modern high strength steels are strengthened and toughened not only by alloy elements addition but also by controlled steel rolling procedure through developing very fine grain constituent. For these kinds of steels, concerns are raised in the growth of the fine grains when it is subject to welding heat, which may offset some advantages. In order to obtain quality welded joint, many work should be done in terms of selecting proper welding materials, optimizing welding technology and developing good weldability of the steels as well.

Because of the limited methods in weld metal strengthening and toughening and the degraded changes in the welding heat-affected zone, it is impossible to keep the properties of the welded joint as good as the base metal, but it is desirable to make them as close as possible. In terms of welding methods of low alloy high strength steel of this grade, though submerged arc welding is reportedly used [1], the most used methods are still gas metal arc welding (GMAW) and shielded metal arc welding (SMAW). The later two methods can exercise a smaller heat input in order to minimize the loss of the strength in heat-affected zone, so they are used in this experiment. In GMAW welding, two commercial filler wires, 1# wire with higher Ni and medium Mn, Cr and Mo and 2# wire with medium Mn, Cr Ni and Mo were employed, both producing over-match but differently alloyed weld metal, while in SMAW welding, one commercial electrode (3#) was used that produced under-match weld metal in strength. Then mechanical tests were carried out and microstructures and the cause of cracking that originated during bending test were examined. The chemical compositions exert an important influence on the strength and toughness of the weld metal. Only the weld metal with moderate Mn, Cr, Ni and Mo content that are very close to the base metal has good comprehensive properties, though the other two weld metals have higher toughness.

## 1. EXPERIMENTAL

The steel used in this experiment has a nominal tensile strength of 700MPa, and mainly contains low carbon, medium amount manganese and molybdenum. The steel plate is 20mm thick and the test pieces are 150mm wide and 500mm long. The edge preparation is single V shaped with a root face of 5mm and the groove angle of 45°.The welds are parallel to the rolling direction of the steel. The first run is made by means of the technology so called double-side formation with one-side welding operation. For gas metal arc welding, the machine is Lincoln Power Wave 455 with a mix of 20% $CO_2$+80%Ar as shielding gas which can cause less loss of alloying elements and produce stabler arc and smoother weld appearance thereby, compared with 100% $CO_2$ as a shielding gas. The filling passes were carried out with the welding parameters welding current about 250A, arc voltage 27V,traveling speed 28cm/min and gas flow rate 18L/min. For shielded metal arc welding, the welding current is about 170A, arc voltage 21V, and traveling speed 15cm/min.

Tensile test on the transverse flattened sample was used for judging weather the strength of the joint is higher than that of the base metal or not by the fracture location. Bending test on the transverse flattened sample was used for assessing the ductility of the joint. Tensile test on the round samples of all-weld-metal was used for determining the strength of the weld metal. Charpy impact test was carried out and the composition of the weld metals was also analyzed. Metallographic analysis was made on the weld metal and the heat-affected zone as well. EPA was used to identify the defect that occurs in the weld metal.

## 2. TEST OF MECHANICAL PROPERTIES OF THE WELDED JOINT

The results of tensile test and bending test on transverse joint are listed in Table 1 and tensile tests on the round all-weld-metal sample listed in Table 2. D is the diameter of bending axis and a the thickness of the sample.

Table 1 Results of tensile test and bending test of the welded joint

<table>
<tr><td rowspan="2">Electrode №.</td><td colspan="2">Transverse tensile test</td><td colspan="4">Bending test (d=3a,120°)</td></tr>
<tr><td>Tensile strength Rm (MPa)</td><td>Fracture location</td><td colspan="2">Face bending</td><td colspan="2">Root bending</td></tr>
<tr><td rowspan="2">1#</td><td>720</td><td>Base metal</td><td colspan="2" rowspan="2">Not qualified</td><td colspan="2" rowspan="2">Not qualified</td></tr>
<tr><td>725</td><td>Base metal</td></tr>
<tr><td></td><td></td><td></td><td colspan="2">d=3a,120°</td><td colspan="2">d=3a,180°</td></tr>
<tr><td rowspan="2">2#</td><td>725</td><td>Base metal</td><td>Face bending</td><td>Root bending</td><td>Face bending</td><td>Root bending</td></tr>
<tr><td>730</td><td>Base metal</td><td>Qualified</td><td>Qualified</td><td>Qualified</td><td>Qualified</td></tr>
<tr><td rowspan="2">3#</td><td>705</td><td>Base metal</td><td colspan="2" rowspan="2">Micro crack</td><td colspan="2" rowspan="2">Not qualified</td></tr>
<tr><td>685</td><td>Near weld</td></tr>
</table>

Table 2 Result of all-weld-metal tensile test

| Electrode № | Yield strength $R_{eL}$(MPa) | Tensile strength Rm(MPa) | Percentage elongation, A(%) | Area reduction Z(%) |
|---|---|---|---|---|
| 1# | 680 | 745 | 20 | 66.5 |
| 2# | 730 | 770 | 19.5 | 66.0 |
| 3# | 620 | 695 | 24.5 | 71.5 |

The impact test results of the welded joint are shown in Fig. 1. The hardness of the joints was inspected with an interval of 0.5mm, and its distribution along the line 2mm below the weld surface across the welded joint is shown in the following figures 2 to 4. Apparently the hardness values well reflect the variations of strength across the welded joint produced with the three welding electrodes.

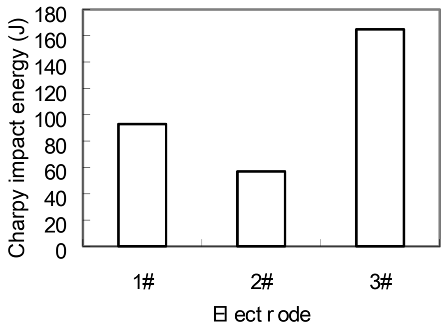


Fig.1 Charpy impact energy at -20℃

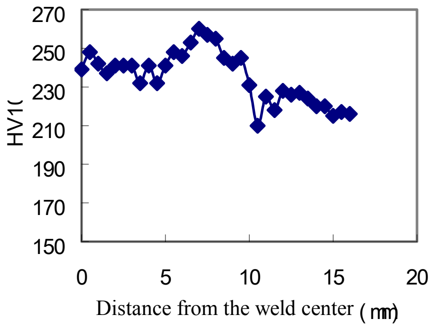


Fig.2 Hardness distribution of 1# joint

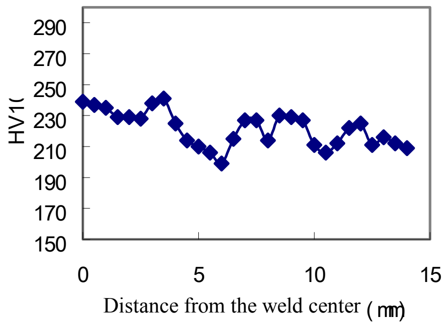


Fig.3 Hardness distribution of 2# joint

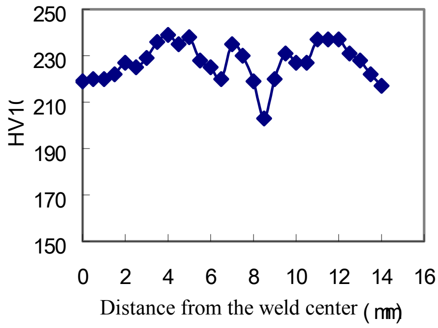


Fig.4 Hardness distribution of 3# joint

The contents of the main elements in the weld metals are shown as Table 3.

Table 3 Composition of weld metals

| Electrode № | C | Si | Mn | Cr | Ni | Mo | S | CE | Pcm |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.043 | 0.37 | 1.20 | 0.100 | 1.78 | 0.40 | 0.012 | 0.462 | 0.177 |
| 2 | 0.063 | 0.40 | 1.28 | 0.260 | 1.18 | 0.25 | 0.0083 | 0.457 | 0.190 |
| 3 | 0.064 | 0.45 | 1.69 | 0.040 | 0.020 | 0.32 | 0.0035 | 0.41 | 0.188 |

The microstructures of weld metal and heat-affected zone are shown in a series of pictures in Fig.6. They are acicular plus prior ferrite in 1# weld metal, bainite in the coarse-grained HAZ, bainite plus ferrite both in the normalized zone and the incomplete normalized zone and bainite in the base metal.



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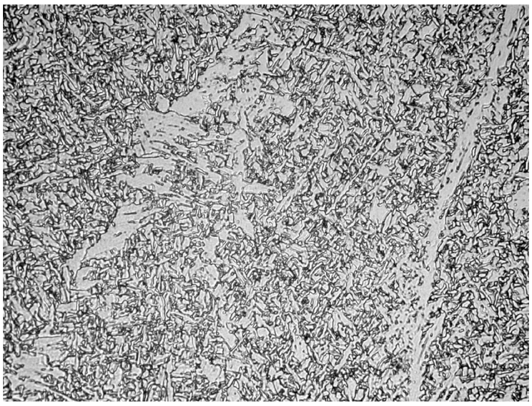
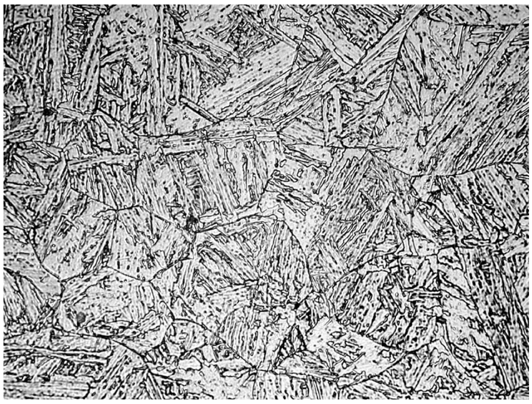
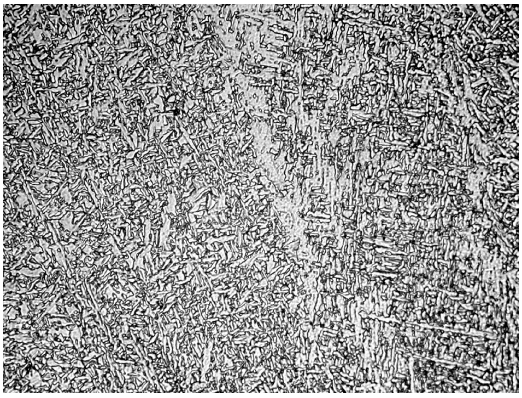
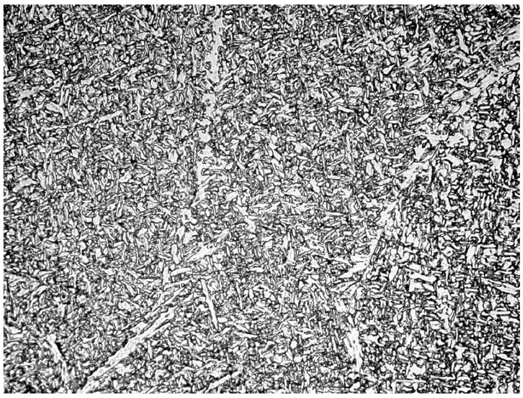
 

Acicular plus prior ferrite　　　　　　Bainite

a) weld metal ×500　　Fig.6 b) CGHAZ ×500

Fig.6 Microstructure of 1# joint

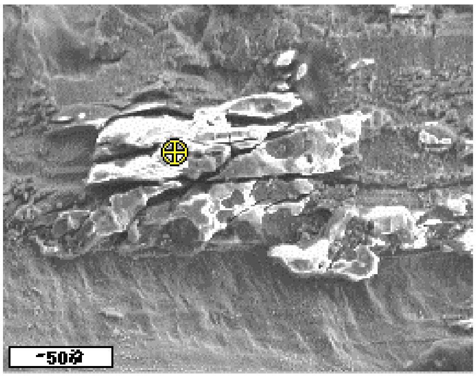
The microstructures of the weld metals of 1# wire and 3# electrode are shown in Fig. 7 and Fig.8 respectively. It is obvious that Fig.8 has narrowest prior ferrite band, correspondingly its weld metal having the best impact toughness.

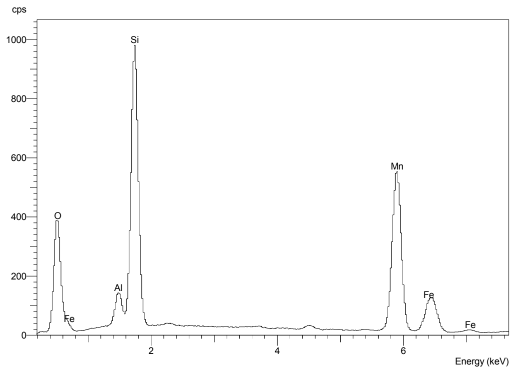
Acicular plus prior ferrite　　　　Acicular plus prior ferrite

Fig.7 2# weld metal ×500　　　　Fig.8 3# weld metal ×500

After bending test, 1# sample was found of two cracks, one on the side of the weld Fig.9 and the other on the bending top face that may originate and propagate during the bending test. For the crack on the side, it is seen to be near the junction of the fusion line and the weld interpass. In the internal surface of the cracks, some oxides were found. X-ray elemental characteristic analysis show the elements are Al in form of $Al_2O_3$ (4.76%), Si in $SiO_2$ (43.64%), Mn in MnO (45.05%) and Fe in FeO (6.53%). The internal surface is kind of free column grain characteristic, implying that the cracks initiated from the oxides slag and lack of fusion.



a) Defect appearance b) Image of the internal surface of the defect




c) Elemental characteristic spectral chart

Fig.9 Analysis on the defect in 1# bending test sample

## 3 DISCUSSION

1) Influence of alloying elements on strength and toughness of weld metal

In order to make a good strength match between the mainly alloying strengthened weld metal and the multi-method strengthened high strength steel, the weld metal should contain more amounts of elements than the base metal. For strength of weld metal, it can be evaluated by the introduction of the carbon equivalent of the weld metal. The carbon equivalents of the three weld metals Pcm and CE are calculated and listed in Table 3 according to relations (1) and (2)[2].

$$Pcm=C+Si/30+(Mn+Cu+Cr)/20+Ni/60+Mo/15+V/10+5B \quad (1)$$

$$CE=C+Mn/6+(Ni+Cu)15+(Cr+Mo+V)/5 \quad (2)$$

CE of weld metals is 0.41%, 0.462% and 0.457% respectively, and correspondingly the strength is 695, 745 and 770MPa. Apparently CE value is suitable for the evaluation of the strength of weld metal.

Comparing 2# and 3# weld metals, both have almost the same carbon content, but 3# weld metal has obviously lower CE value, and its strength is lower. For 1# and 2# weld metals, both have approximate CE value with obvious variation in carbon content. 1# weld metal possesses hither strength than 2#, indicating that carbon content is more significant in promoting weld metal strength.

It is not easy to evaluate toughness of the weld metal simply by some equations since many factors can place an influence on it. However it is no doubt that too high a Pcm value is deleterious to the crack resistance of the weld metal [2], while too low a Pcm value may bring weld metal with a large portion of prior ferrite which also contribute to low toughness. In these senses, an optimum Pcm value exists for a high toughness. It also should be pointed out that sulphur content, and nickel content can have great influence on toughness of the weld metal [3], which is the explanation for 3# weld metal having the highest impact energy of 170J and 1# weld metal having higher impact energy than 2#.

2) Influence of strength on bending test results

Among the three weld metals, only sample 2 is qualified for the bending test. Sample 2 is over-matched and is the closest in chemistry to the base metal producing more uniform composition and thereby more uniform mechanical properties in the weld metal. In the bending test, this welded joint can undergo a more uniform deformation in the whole joint and will not break. When the strength of the weld metal is too low and there is a large difference in chemistry between the weld metal and base metal, the inverse process will happen and easily result in unqualified bending properties.

3) Frequent defects in GMAW weld metal

In GMAW welding under the shielding of the mixture of 20%$CO_2$ and 80%Ar , some oxides like manganese oxide, silicon oxide inevitably form in the melting pool and move to the surface and form film oxides stick to the surface of the weld. They are not easily detachable and hence likely to cause large oxide interpass defects if they are not properly removed by grinding.

Lack of fusion in gas metal arc welding can occur due to excessively low or excessively high deposition efficiency. In the first case the base metal is not sufficiently melted, because the arc is too weak or the welding speed too high. In the case of high deposition efficiency, the arc burns on the weld pool and the transfer of heat to the weld groove sidewalls or to the former welding passes is no longer caused by the arc itself, but only by the convection in the weld pool.

The viscosity and the surface tension of the liquid weld metal determine how far the weld pool build up in the groove to some extent. It is also known that the manganese-silicon ratio has an influence on the flow properties. With iron pools both values are mainly influenced by the sulphur and oxygen content. The surface tension falls with increasing oxygen content and at the same time the weld metal becomes more fluid [4].

**4. CONCLUSIONS**

Through the test on 700MPa grade steel welding, the following conclusions can be drawn.

1) Strength of the weld metal is a first priority in terms of welding HSLA steel. A properly

over-matched weld is beneficial to the bending property of the welded joint, while under-matched weld metal is more likely to result in unqualified bending properties.

2) High amount of Mn and Ni in weld metal can produce weld metal high toughness. A balanced and moderate content of alloying elements Mn, Ni, Mo and Cr make the weld metal chemically close to the base metal, thus leading to good comprehensive mechanical properties.

3) For the weld metal of 700MPa grade or above steels, defects in the weld metal such as lack of fusion between interpasses of weld or fusion lines or slag or large size inclusions that easily occur in GMAW welding generally become more critical in initiating the failure of the weld metal, so proper welding procedure should be taken to avoid there kinds of defects.

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## REFERENCES

1) J.P.SNYDER,II AND A.W.PENSE. Welding Journal, 7,(1982):p.201-s.
2) S. ENDO, M. NAGAE, M. ITOH, T. SUGINO and S. NARUSE. United States Patent 5,272,305,(1993).
3) PH.BOURGETS,L.JUBIN and P.BOCQUET. Mathematical Modeling of Weld Phenomena. The Institute of Materials, London (1993): p 201.
4) R.KILLING and H.HANTSCH, Welding research Abroad, 5, (1995): p.31.