Study on filler metal (Ni-Fe-C) during GTAW of WC-30Co to 45″ carbon steel

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In this study, WC-30Co cemented carbide is welded to carbon steel by the gas tungsten arc welding (GTAW) using Ni-Fe filler metal and Ni-Fe-C filler metal. The butt joints manifest more embrittling η-phase carbides with Ni-Fe filler metal, while less even no η-phase carbides with Ni-Fe-C filler metal. The η-phase carbides morphology and formative factors were further discussed using Backscattered Electron Imaging (BEI) method; Electronic probe microanalysis (EPMA) is used to determine the distribution of elements Ni, Fe, C, W and Co across the HAZ (Heat Affected Zone) near WC-30Co/welded-seam interface. The hardness profile is determined using micro-hardness measurements and bend strength value of butt joint with different filler metal is tested by four-point bend strength test. The hardness profile and bend strength value agree with the information obtained from microstructure analysis, BEI analysis and X-rays phase analysis very well. The results show: (1) butt joint of WC-30Co/carbon steel can be obtained using GTA with Ni-Fe-C filler metal; (2) the addition of carbon content to Ni-Fe filler metal leads to less even none η-phase multi-carbides strongly, and mechanical property of butt joint can be improved.

1. Introduction

Weldment of WC-30Co cemented carbides and 45″ carbon steel. was used widely due to its high hardness (especially in high temperature), high strength with good erosion-resistance and chemical resistance [1]. At president, research was mainly focused on overlaying welding or thermal spraying without filler metals (conventional plasma spraying in air, high energy gas flame spraying and low pressure spraying), pure Ni or Ni-Fe filler metals [2–8]. Among them, braze welding and diffusion welding were two major methods to join cemented carbide and carbon steel. However, low service temperature and weak bond strength limited application of braze welding [9]. In diffusion welding of cemented carbide to carbon steel, it was always recognized that reaction layer including η phase of $(Fe,W)_3C$, $(Fe,W)_6C$ [10, 11] was formed inside WC-Co cemented carbide near interface (also called Heat Affected Zone, HAZ), which was the major disadvantage for diffusion welding of cemented carbide to carbon steel. Moreover, size of base metals was also limited in diffusion process.

GTAW technique used to WC-30Co/45 steel welding had been investigated using pure Ni, Ni-Fe alloys as filler metals and well-metallurgy butt joint was confirmed [12]. However, When using pure Ni as filler metals, although η phase was not formed near WC-Co/welded-seam interface, cost was high with low hardness of butt joint; When Ni-Fe filler metals were used, embrittling η phases were easily formed resulting in weak mechanical behavior.

Using GTAW technique, Ni-Fe-C filler metals were developed in order to decrease embrittling η phases and improve mechanical properties.

2. Experimental

GTAW of WC-30Co cemented carbide (sintering with 7 μm Fisher sub-sieve sizer (FSSS) WC powder and 2 μm FSSS Co binder) to 45″ carbon steel was investigated. The hardness (an average pressure on the cone face of a rigid rod at its impact indentation into the surface layer of a thick plate) of WC-30Co base metal was 81.5 HRA, and the bend strength was 2000 Mpa.

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TABLE I Chemical content of WC-30Co cemented carbide, 45″ carbon steel & Filler metal (wt.%)

Materials	C	N$_1$	Co	W	S	P	Fe
45 STEEL	0.45	–	–	–	<0.003	<0.003	Balance
WC-30Co	4.29	–	30	65.71	–	–	–
Alloy 1	0.01	55.33	–	–	<0.003	<0.001	Balance
Alloy 2	0.41	55.30	–	–	<0.003	<0.003	Balance
Alloy 3	0.62	34.70	–	–	<0.003	<0.004	Balance
Alloy 4	0.81	54.78	–	–	<0.003	<0.004	Balance

Ni-Fe-C alloys were developed as filler metals. The chemical content of base metals and Ni-Fe-C filler metals were shown as Table I.

Base metals (WC-30Co and carbon steel) was cut into semi-circle, and groove angle was 30°. The configuration of GTAW process was illustrated in Fig. 1.

Four-point bend strength test (transverse rapture strength) was also carried out using WE-10A (0–5 tons) type Dynamic Mechanical Analysis system. The size of test specimen was 4 × 6 × 40 mm. Curvature radius of the sample was 0.1–0.3 mm, and chamfer angle in head face was 45° × c (0.1–0.3 mm).

3. Results and discussion

3.1. Microstructure & η phase's morphology

Butt joint of WC-30Co/45 steel with well-metallurgical bonding was obtained with Ni-Fe filler metal and Ni-Fe-C filler metal for all samples, free from faults such as porosity (air hole), fine hair crack and slags etc. The macro-structure was shown in Fig. 2.

Microstructure near WC-30Co/welded-seam interface of butt joint with Alloy1, 2, 3 and 4 as filler metals respectively was illustrated in Fig. 3. The sample position for analysis was shown in upper graph of Fig. 3a (rectangular part).

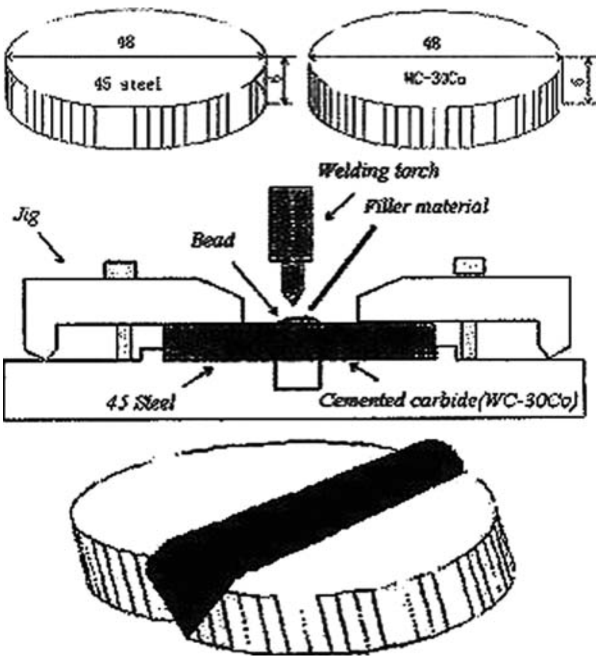


Figure 1 Configuration for GTAW of WC-30Co to 45″ carbon steel.

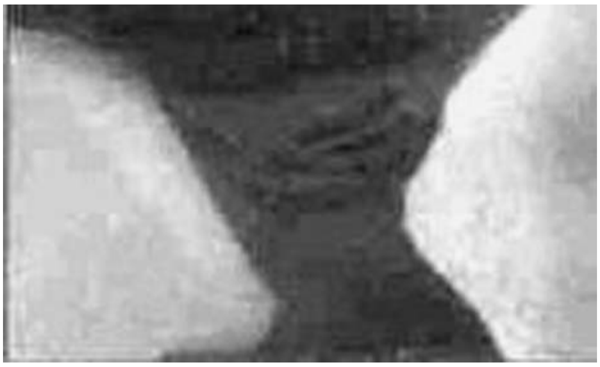


Figure 2 Macro image of butt joint for WC-30Co/45 steel 12×.

Thick and large-sized η phases were formed near WC-30Co/welded-seam interface using Alloy 1 as filler metal (see Fig. 3b), and maximum layer was up to 100 μm; Thin and medium-sized η phases were formed near WC-30Co/welded-seam interface when using Alloy 2 as filler metal (see Fig. 3c); Fine and small-sized

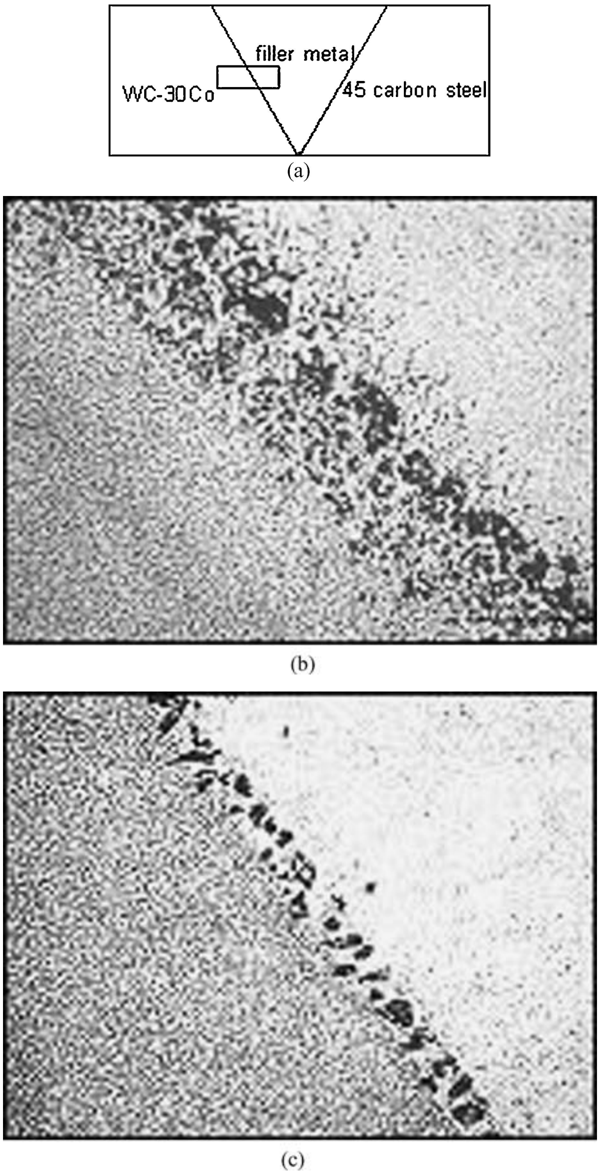
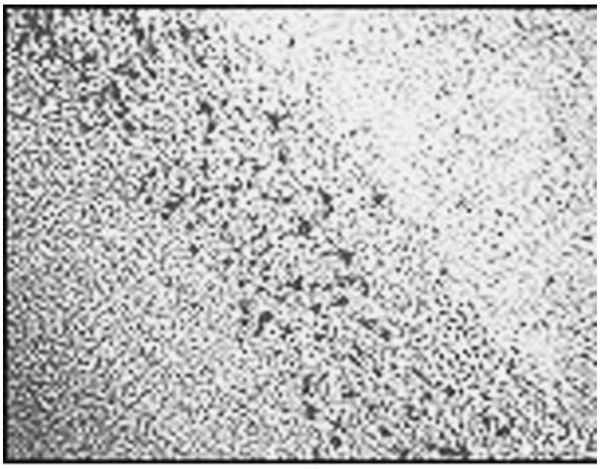
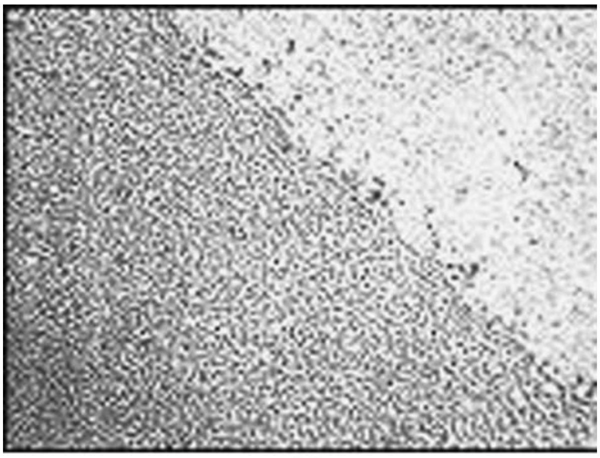


Figure 3 Microstructure distribution with different filler metal. (*Continued*)



(d)



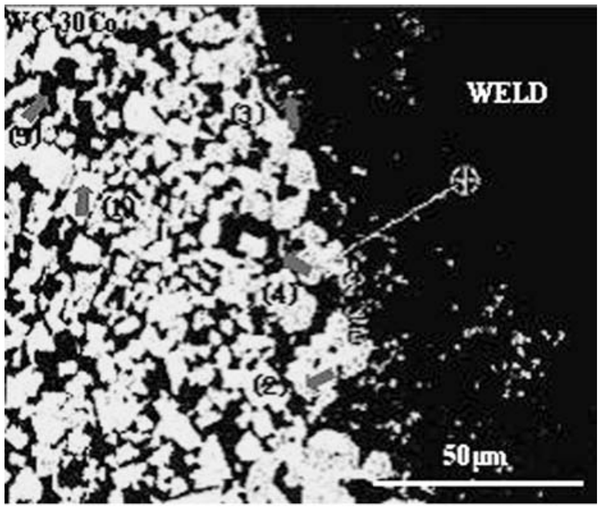
(e)

Figure 3 *(Continued)*

η phases were formed in this region using Alloy 3 as filler metal (see Fig. 3d); however, no η phases were formed in this region while using Alloy 4 (see Fig. 3e) as filler metal. Columnar crystals were also observed near welded-seam. That is to say, if carbon content increased in filler metals, η phases formed near WC-30Co/welded-seam interface varied from "thick and large-sized" to "thin and small-sized" even "no η phases" formation.

Microstructure of butt joint depended to a great extent on ingredient in filler metal when welded with the same welding layer. Generally speaking, carbon content might diffuse from WC-30Co into welded-seam because of its high concentration gradient for carbon. However, when using Alloy 2, Alloy 3 and Alloy 4 (Ni-Fe-C alloy) as filler metal, carbon diffusion was blocked with the addition of carbon content, by contrast, when welded with Alloy1 (Ni-Fe alloy), carbon content was too low to limit carbon diffusion which resulted in hard and embrittling η phase emerging. η phase's morphology was illustrated in Fig. 4, where WC particle, η phases, Needle carbide, Matrix based on FeNi and Co matrix near WC-30Co/welded-seam interface were observed.

The distribution of elements Ni, Fe, C, Co and W near WC-30Co/Welded-seam interface was studied in 54.3-μm distances between WC-30Co and welded-seam. Results indicated: average content in small-sized



(1)WC particle; (2)η phases; (3)Needle carbide; (4)Matrix based on FeNi; (5)Co matrix in WC-30Co system

Figure 4 BEI image near WC-30Co/ Welded-seam interface when using Alloy 1 as filler metal (Ni-Fe filler metal).

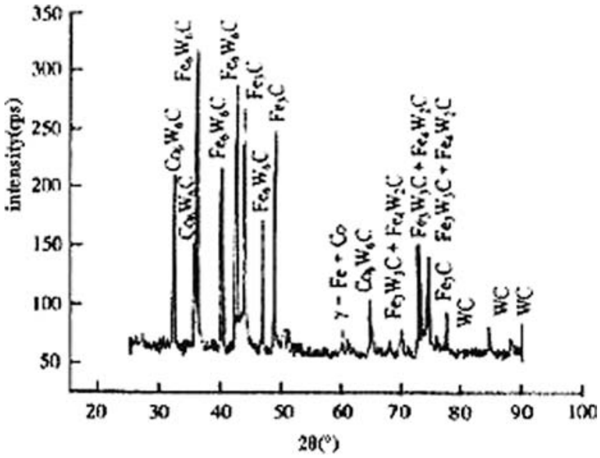


Figure 5 Primary phase analyses.

η phases was 12.57%Fe, 71.18%W and 3.34%Co; average content in large-sized η phase was 15.22%Fe, 74.07%W, 3.67%Co and 2.66%Ni. On the other hand, according to theory calculation, average content of Fe and W in M_6C and $M_{12}C$ (M stands for Fe, Ni or Co) was nearly 23.2% and 75.30% respectively. Therefore η phase might be such multi-carbides as M_6C and $M_{12}C$, which was further confirmed by phase analysis showed in Fig. 5, primary phase near WC-30Co/welded-seam interface was Co_6W_6C and Fe_6W_6C, with a little Fe_3W_3C and Fe_4W_2C, Fe_3C was discovered also in this region. η phase was just M_6C, $M_{12}C$ type multi-carbides.

3.2. Elements distribution & phase diagram analysis

Interfacial diffusion (Ni, Fe, C, Co) was realized through element diffusion across WC-30Co/welded-seam interface. Plate Model was brought forward by Fisher. The following equation disclosed element

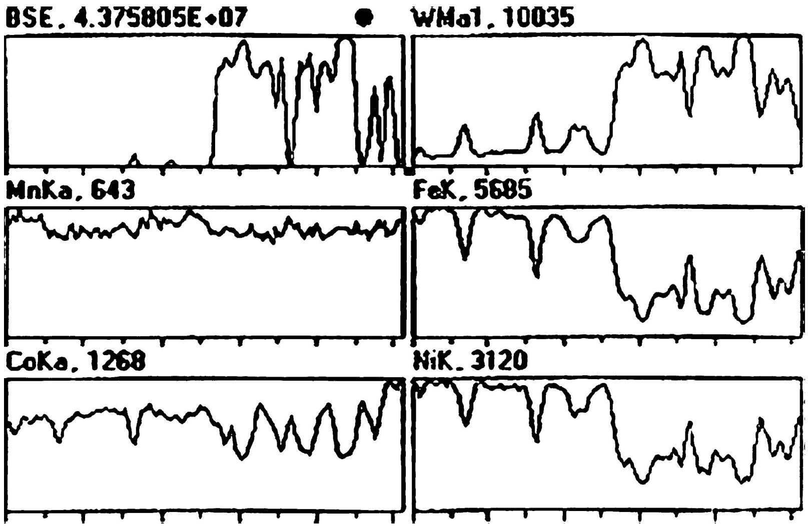


Figure 6 Content graphs for elements Ni, Fe, W, Co and Mn. (horizontal axis stands for distance to test point/μm; Vertical axis stands for content of contents).

distribution at crystal interface

$$\left(\frac{D'}{D} - 1\right)\frac{\partial c}{\partial t} = D'\frac{\partial^2 c}{\partial y^2} - \frac{D\partial c}{K_a \partial x} \qquad (1)$$

This formula was the fundamental for interface diffusion theory. In order to simplify, we proposed following hypotheses:

(1) diffusion behavior of element was independent of others, and this study was carried out abide by the law of Mass diffusion;
(2) crystal lattice diffusion was omitted.

Based on the above hypotheses, by Equation (1), we had,

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial t}\left[D(c)\frac{\partial c}{\partial x}\right] \qquad (2)$$

diffusion coefficient $D(c)$ was defined as followed,

$$D(c) = -\frac{1}{2t} \bullet \frac{dx}{dc}\int x dc \qquad (3)$$

where $D(c)$ denoting the comprehensive effect of diffusion coefficient and diffusion time on difusibility of elements. Parameter t could be determined as follows [8].

$$t_H = f_3 \frac{q/v}{\lambda(T_m - T_0)} \qquad (4)$$

When using Ni-Fe (carbon content: 0.01%) as filler metal, the distribution of elements Ni, Fe, C, Co, W contents near WC-30Co/Welded-seam interface was shown in Fig. 6. Thus interface diffusion model was constructed by MATLAB curvefitting technique (Third-degree polynomial curve could be used for Quasi-concentration distribution). Combined with Plate model, diffusion coefficient where thick and large-sized η phases were formed could be calculated, and diffusion coefficient of elements Fe, Co and Ni in different layer distance near WC-30Co/welded-seam interface was listed in Table II.

From the results we could see that element Fe manifested strong diffusibility in matrix near η phases. Concentration for element Fe in η phase was very high, thus higher concentration gradient would enhance opportunity and ability of element Fe to diffuse from welded-seam to W-Co-C system which existed in WC-30Co. On the other hand, W-Fe-C system (η phase) could come into being because of carbon-poor and element Fe taking the place of element Co. That is to say, carbon-poor phenomenon of W-Co-C system resulted from carbon diffusion and high Fe diffusibility was two vital factors inducing to η phases.

In generally, phase of W-Co-C system consisted of γ phase and WC phase, however, when high-carbon phenomenon appeared, carbon content would dissociate from nomal W-Co-C system (γ + WC) to (γ + WC + C) (see Fig. 7). On the other hand, while concentration gradient of carbon was high enough, the carbon in γ phase would diffuse from W-Co-C system to welded-seam, followed by diffusion of carbon from WC to γ phase, thus carbon-poor phenomenon of W-Co-C system appeared. Subsequently, with the diffusion of elements Fe or Ni, W-X(Fe, Co, or Ni)-C system would be formed. From the phase diagram of W-Ni-C, W-Co-C system (see Fig. 7), area of normal phase γ + WC in W-Ni-C diagram was very large, that is to say, it was

TABLE II Diffusion coefficient of elements Fe, Co and Ni of different layer distance at WC-30Co/welded-seam interface

x(μm)	$D(c)_{Fe}$	$D(c)_{Co}(\times 10^3)$	$D(c)_{Ni}$
5	1.1158	0.6883	1.4722
10	1.0768	0.6642	1.4206
15	1.1771	0.7316	1.5653
20	1.1424	0.7100	1.5190
25	1.1025	0.6852	1.4660
30	1.1918	0.7435	1.5911
35	1.1568	0.7217	1.4454
40	1.1162	0.6954	1.4902

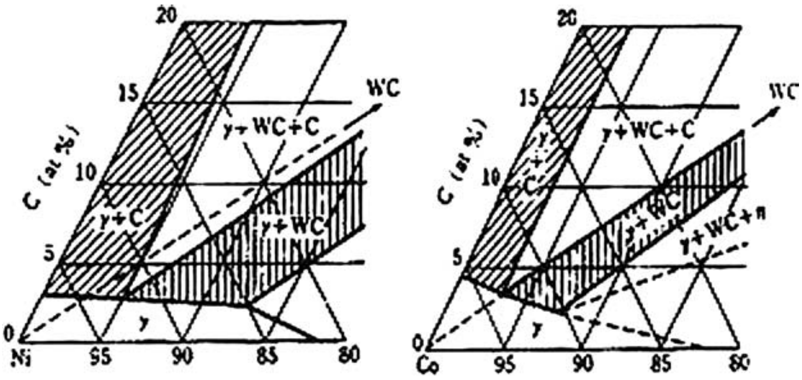


Figure 7 State diagram for W-Ni-C and W-Co-C system.

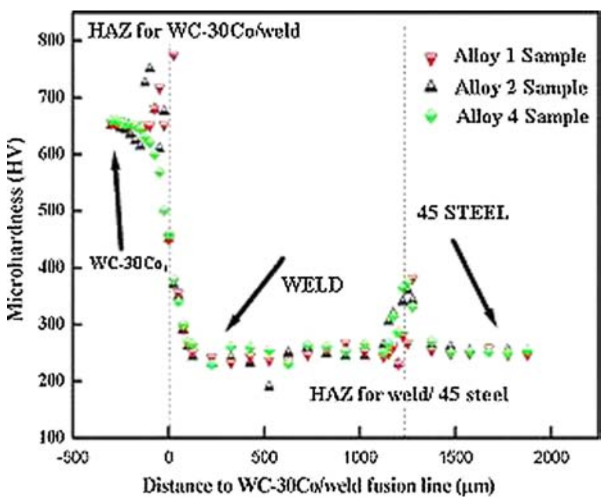


Figure 8 Graph for micro hardness and distance.

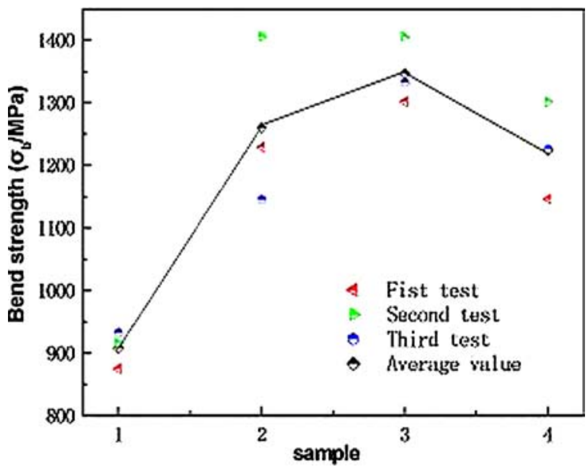


Figure 9 The relation of bend strength and Ni-Fe-C filler metal.

hard for η phases to form even while the condition of carbon-poor phenonenon; by contrast, area of γ + WC in W-Co-C was smaller, that means there was a great tendency for η phases formation. Among the three systems, area of γ + WC in W-Fe-C was the smallest one. Once the carbon-poor phenonenon emerged, the normal γ + WC phases would be destroyed easily.

Therefore, η phases were easily formed in W-Fe-C system than that in W-Co-C even in W-Ni-C system, which was the reason that η phases were easily formed under the condition of more Fe and less Ni in W-Co-C system.

3.3. Micro hardness survey

Result on micro hardness measurement of butt joints was showed in Fig. 8. From the graph that micro hardness of WC-30Co (660 $HV_{0.2}$) was higher than that of welded-seam (240 $HV_{0.2}$) significantly.

In details, for Alloy 4 sample, smooth curve of micro hardness were achieved from welded-seam to WC-30Co; by contrast, Alloy 1 sample and Alloy 2 sample achieved a serial of higher hardness values near WC-30Co/welded-seam interface. This would owe to η phases formation. On the other hand, with increase of carbon content in Ni-Fe-C alloys, micro hardness of welded-seam increased to some degree. The smooth curve of micro hardness also manifested well metallurgical bonding was obtained across the whole butt joint.

3.4. Bend strength

Bend strength test was used to estimate the properties of hare metal articles (including welding workpiece) besides micro hardness. According to JISR-1601-1995, referenced GB/T 14452-93 national standard, four-point bend strength test was carried out. The bend strength value of butt joint varied with different filler metal, which was shown in Fig. 9.

From bend strength analysis, we could see: with the addition of carbon content, bend strength could be improved significantly. Under the condition of filler metal designed by us,

4. Summary and conclusions

By GTAW technique, well-metallurgical joint of WC-30Co/45 steel has been obtained using Ni-Fe-C alloys as filler metals. The reasons for embrittling η phase formation are investigated. On this basis, new welding technique for butt joint of WC-Co/carbon steel based on GTAW technique is bought forth, welding wire Ni-Fe-C used for WC-Co/carbon steel could be developed. The conclusions are as follows:

(1) Embrittling η phase formed near WC-Co/welded-seam interface is M_6C, $M_{12}C$ type multi-carbides when using Ni-Fe filler metals. The addition of carbon content to Ni-Fe filler metal can lead to less even none η-phase carbides.

(2) The carbon-poor phenomenon of W-Co-C system resulted from carbon diffusion and strong Fe diffusibility are the two formative factors inducing to η phases.

(3) The micro-hardness of butt joint is changed smoothly, bend strength can be improved by addition of carbon content to Ni-Fe filler metals and reduce of η phases near WC-30Co/welded-seam interface.

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