

Microstructures and mechanical properties of a martensitic steel welded with flux-cored wires

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Abstract This study was focused on wear-resistant material prepared by CO₂ GMAW method to basically determine the alloys and hardfacing technology which could be employed into mining equipment. Three flux-cored wires with different chemical compositions, marked by DM-I, DM-II and DM-III were used in welding a martensitic steel for the comparison of the microstructures and mechanical properties of the welding metals and HAZ. The results show that DM-I weld metal contains martensite plus other reinforced phases, while both DM-II and DM-III alloys lead to mainly martensitic microstructures with little precipitates. Among all of the tested materials the DM-I alloy has the highest hardness and wear resistance but the lowest impact toughness among the experimental weld metals. Meanwhile, the hardness, impact toughness and wear resistance of the DM-II and DM-III alloys are close to those of the base metal but the DM-III is not as strong as DM-II. Dimples can be found on the impact fracture of the weld metals, but the steel fracture consists of both cleavage and dimples. Thus HAZ has less risk for cracking than the welds, and the DM-II wire which produces the weld having identical mechanical properties to the base metal is suitable for further application.

Keywords Hardfacing · Microstructure · Mechanical property · Flux-cored wire · GMAW

1 Introduction

Wear of materials occurs frequently in coal mining industries. To solve this problem, numerous hardened metals and advanced technologies are used to resist the wear from hard substances such as coals, rocks or ores. Surfacing with hard filler metals or alloys is one of the most effective methods for maintenance of the worn materials, permitting prolonged equipment lives. By now, remarkable progress has been made in developing efficient and flexible surfacing technology to improve both wear and corrosion resistance of materials, and lead to wide

applications in industry (Menon 1996; Prasad et al. 1998). However, for those martensite-hardened steels, filling hard metals with different compositions is considered as a great difficulty due to a strong tendency of cracking. To obtain a crack-free hard surface both chemical composition and hardfacing technology need to be carefully designed.

Although the influences of chemical compositions of filler metals on the microstructure of the deposit layers are important to determine the mechanical property and performances, much attention has also been paid to develop filler metals to improve the compatibility to the base materials, which might be one of the main problems in both surfacing and laser cladding, and requires the suitably designed composition of the coating alloys (Zollinger et al. 1998). Examples lie in the works on the influence of Cr, Nb and C on the microstructure as well as hardness and wear resistance of deposit layers on nickel-based alloy (Su and Chen 1997; Kesavan and Kamaraj 2010). Other authors promoted different iron-based crack-resisting filler alloys, showing potentially advantageous performances of the

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hardened surfaces, among which carbide-forming elements are mostly considered to use for high hardness of the workpieces (Ingis et al. 1992; Wang et al. 2004; Yang et al. 2011, 2013; Zhang and Ren 2004). In recent years, rare earth elements are found in refining microstructures of hardfacing metals (Hao et al. 2011a, b). For those hardened surfaces, different alloy systems lead to a great diversity in wear behavior and performances, mainly depending on the microstructures (Wu and Wu 1996; Agarwal and Dahotre 1998; Heath and Skora 1998; Kim and Kim 1999; Przybylowicz and Kusinski 2000).

For an iron-based alloy system, element C, Cr, Mo or V are usually added to increase the hardness and wear resistance of the coatings, which also leads to great changes in other performances. Especially for a martensitic base metal, surfacing with hard alloys has a high risk of cracking. Therefore the microstructures and mechanical properties of a hardened base metal surfaced with different alloys remain much interesting for scientists and engineers. Herein, three flux-cored weld wires are used in surfacing a hardened steel by comparison of the microstructures and mechanical properties to obtain further understanding of the effects of alloying elements and expand industrial applications of surfacing technology.

2 Experimental materials and methods

A hot-rolled low-carbon martensitic steel in delivery state was employed as base metal with chemical composition listed in Table 1 and the Rockwell hardness was around 40HRC. The steel plate was machined into specimens of the dimension 1600 mm × 160 mm × 40 mm with the Y-type grooves made by the angle of 90°. Then CO₂ GMAW method was used in welding these specimens. The technological parameters were chosen as the output secondary voltage and electric current are, respectively, 30 V and 200 A; the gas flux 7.0 mL per second, and the welding speed was controlled by 3.0 mm/s. Three flux-cored welding wires with the diameter 1.2 mm were chosen as the filling metals, and the compositions of the deposited iron-based alloys numbered with DM-I, DM-II and DM-III, are shown in Table 2. The samples were carefully processed to ensure that microstructure observation and mechanical property test can be performed exactly within the corresponding zones. Optical microscope and Shimadzu SSX-550 SEM were used for the microstructure

Table 1 Chemical composition of the tested steel (wt%)

C	Si	Mn	Cr	P	S	Ti	B
0.17	0.30	1.45	0.19	0.015	0.006	≤0.02	≤0.0018

observation of the weld metals and HAZ, and thin foil specimens of the weld were prepared and observed on TEM. The phases contained in the weld metals were also analyzed by XRD method.

Rockwell hardness was tested from the centerline of the weld towards the base metal. The impact toughness of each zone is tested at ambient temperature by using the specimens with U notches prepared from the welded steel. Wear experiment which is schematically shown in Fig. 1, was carried out by using the cylinder specimens with the dimension $\phi 5$ mm × 10 mm moving on the abrasive papers of 400 mesh for different distances, and then mass losses of these specimens were measured.

3 Results and discussion

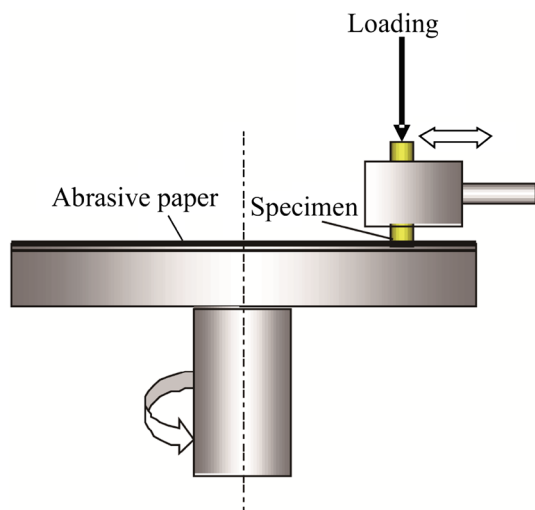
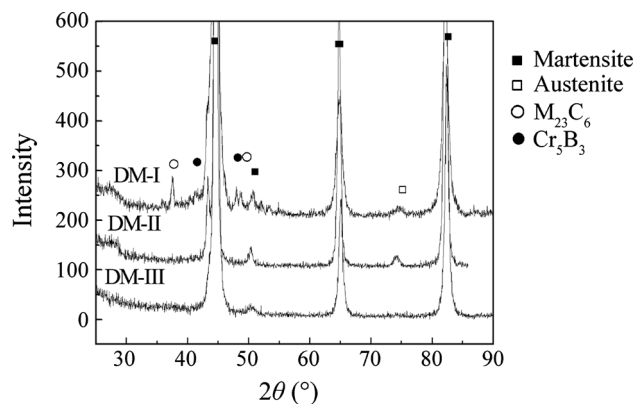
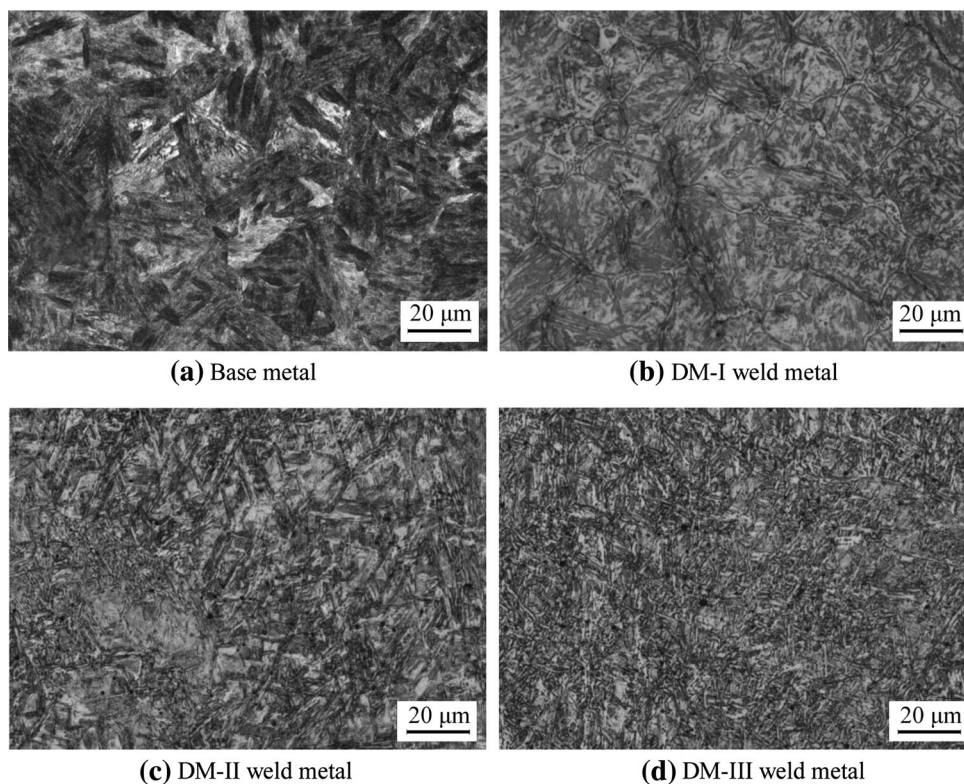
3.1 Microstructures

Figure 2 shows the microstructures of the martensitic steel and the weld metals, respectively, with the wires DM-I, DM-II and DM-III. The initial microstructure of the steel is mainly low-carbon martensite as indicated in Fig. 2a. The weld metals are distinguished from the base metal in microstructures due to different chemical compositions. Figure 2b shows DM-I weld microstructure, in which carbides form on the grain boundaries, and precipitation also occurs within the grains. Addition of relatively much alloying elements, Cr, Mo and B makes the deposited alloy DM-I have proeutectoid composition, which leads to the typical solidified microstructure with equiaxed grains surrounded by carbides or other secondary phases. Both of Fig. 2c, d show similar morphologies of the martensite microstructures, except that the microstructure in Fig. 2d is finer than Fig. 2c. The DM-II alloy contains similar percentages of C, Si and Mn to those of DM-III but more contents of Cr and Mo than DM-III, which causes more precipitates in DM-II alloy. The phase constitutions in the three alloys can be qualitatively characterized by XRD method. As shown in Fig. 3, the results indicate that the alloy DM-I produces not only the hardening martensite, but also M₂₃C₆-type carbides and boron compound, which contributes greatly to high hardness of the weld, whereas the DM-II and DM-III weld metals contain almost identical phases with little carbides or other secondary compounds found.

By TEM method, the microstructures of the DM-I and DM-II weld metals are compared in Fig. 4. For the DM-I weld, martensite with fine sub-grains and twins can be observed concurrently with carbides as shown in Fig. 4a, whereas the microstructures for the DM-II weld and the base metal is martensite that mainly consists of dislocation.

Table 2 Chemical composition of deposited metals (wt%)

Element	C	Mn	Si	Cr	Mo	V	B	P	S	Fe
DM-I	0.470	0	0	5.000	1.230	0.120	0.351	0.010	0.014	Balance
DM-II	0.120	1.352	0.570	3.200	0.980	0	0	0.015	0.012	Balance
DM-III	0.110	1.800	0.610	1.960	0.490	0	0	0.016	0.005	Balance

**Fig. 1** Schematic diagram of the wear test**Fig. 3** XRD patterns for the weld metals with DM-I, II and III flux-cored welding wires**Fig. 2** Microstructures of the weld metals and the base metal

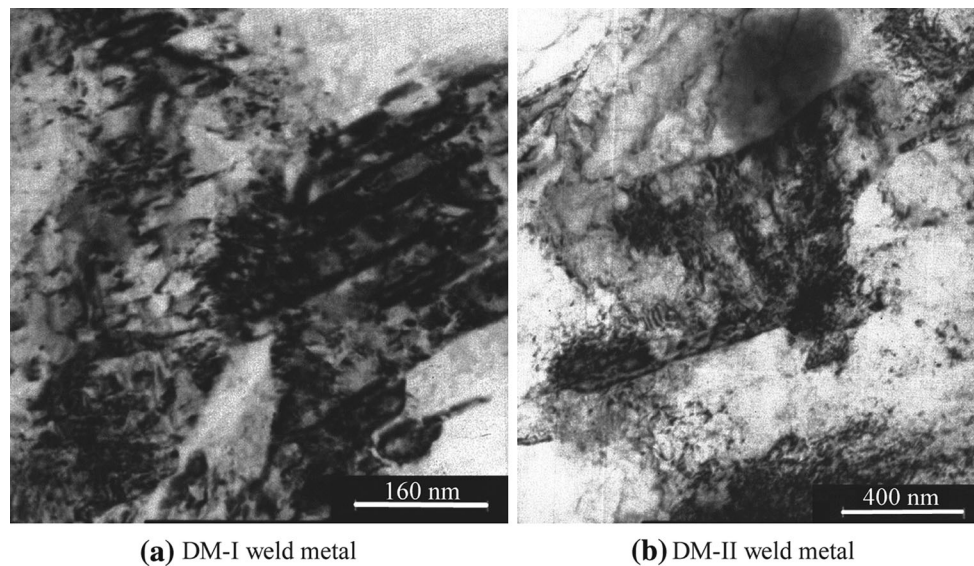


Fig. 4 TEM images of the microstructures of weld metals showing precipitates and dislocations in the subgrains

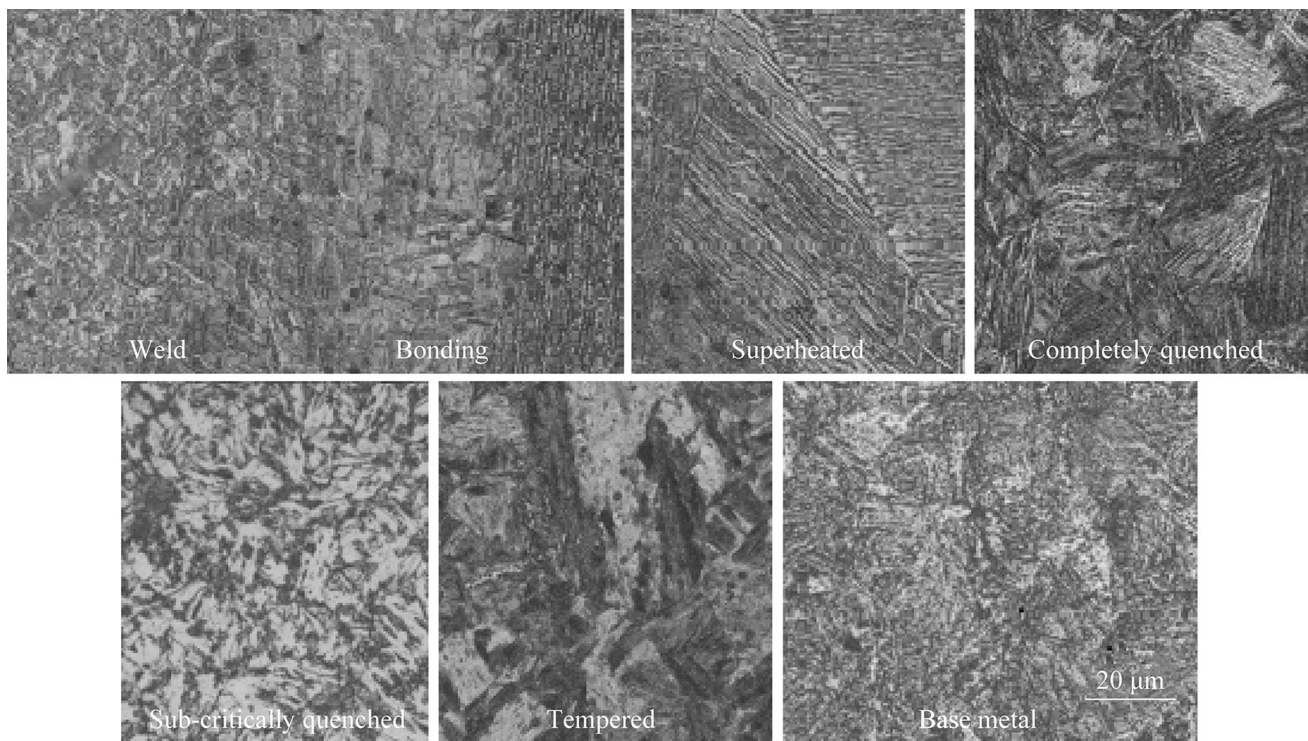


Fig. 5 The microstructures of HAZ for the steel welded by DM-II wire

The microstructures of HAZ is shown in Fig. 5. Observation on the microstructures of HAZ shows different characteristics due to the highest temperatures locally reached during welding. Welding bond that is adjacent to the weld differs from the weld metal where solidification occurs from the base metal where only

solid transformations take place. Martensitic transformation occurs in the superheated zone and completely quenched zone since both of the zones are completely austenized and fast cooled, which are easily distinguished by the grain size. The completely quenched zones consists of finer martensite than the superheated

zone due to the temperature that is slightly higher than A_{c3} . There is a narrow fine-grained zone adjacent to the completely quenched zone where the steel is locally heated up to the temperature range between A_{c1} and A_{c3} and then quenched, so that dual-phased microstructure (ferrite + martensite) can be observed, which is indicated as the subcritically quenched zone. As the temperature is lower than A_{c1} , the initial martensitic structure is somewhat tempered.

3.2 Mechanical properties

Figure 6 indicates the hardness and impact toughness distribution along with the weld metals and HAZ. The weld deposited with DM-I alloy shows the highest hardness among the three depositing metals, whereas the DM-II weld which is nearly identically hard to the base metal, is approximately 5HRC higher than DM-III in hardness. Then the DM-II alloy is suitable for the requirement of the same

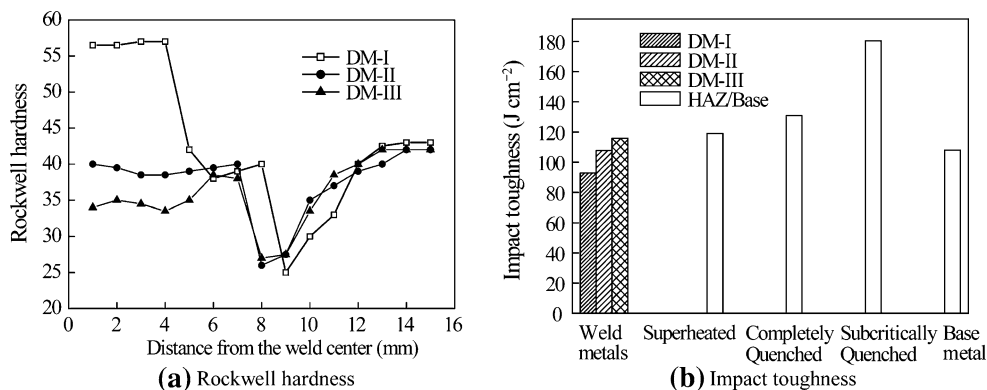


Fig. 6 Mechanical properties of the weld metals and HAZ

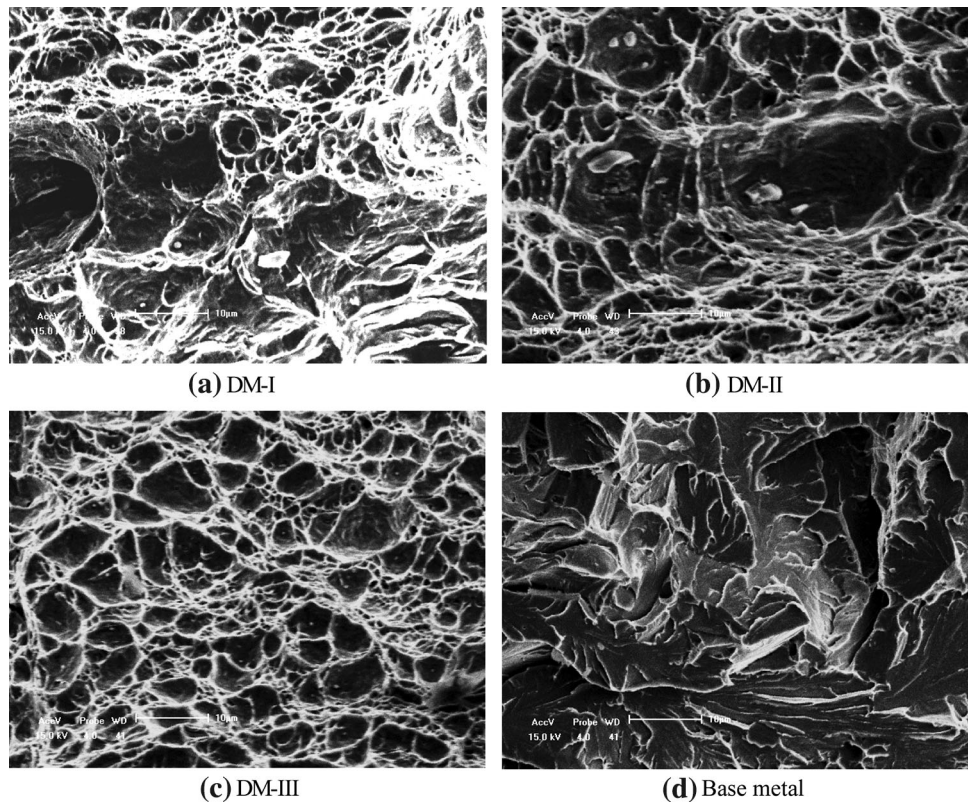


Fig. 7 Fractography for impact samples of the weld metals and base metal

hardness for the weld and base metal. In the HAZ, there is a softened zone located 7–10 mm away from the central line of the welds. This softening effect is resulted from the subcritical temperature reached in the welding so that the dual phase microstructure is formed.

The impact toughness of the weld metal is dependent on the local hardness. The DM-I weld which is the hardest has the lowest toughness among the three welds, and obviously lower than that of HAZ and the base metal. However, the highest toughness appears at the incompletely-quenched zone where the formation of two phases, ferrite + martensite, increases the resistance to crack propagation. Although the superheated zone has coarsened grains, the impact toughness is a slightly higher than the base metal.

The fracture observed via SEM on the impact samples of the three weld metals and the base metal are shown in Fig. 7. For DM-I weld as shown in Fig. 7a, crack propagates in a combined mechanism with inclusions observed, indicating mixture of dimples and cleavage characteristics. Dimples are mainly formed on the fracture of both DM-II and DM-III welds, except that the dimples are more uniform and smaller in DM-III weld. The experimental steel that did not experience a heat cycling during welding is not strong in resisting crack propagation.

Figure 8 shows the comparison of wear resistance of the three depositing metals and the base metal with respect to the abrasion distance. The hardest DM-I alloy display the lowest mass loss, i.e. the highest wear resistance, but the mass losses of DM-II and DM-III alloys are identical to that of the base metal, although the hardness of DM-III alloys is lower. Wear resistance correlates with the hardness as well as other properties such as toughness due to the fact that wear consists of micro-fracture depending upon the toughness of the materials. Thus the increment in the impact toughness of DM-III compensates for the decrease in wear resistance resulted from the reduction of hardness.

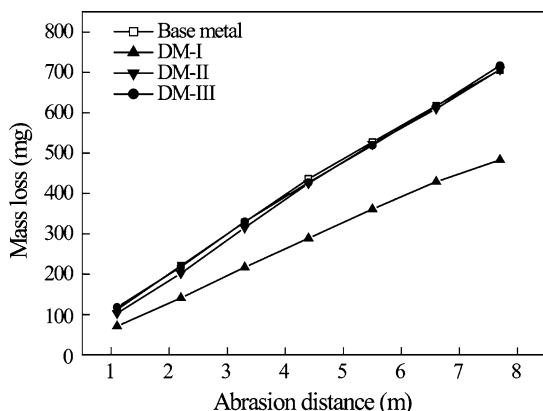


Fig. 8 Comparison of wear resistance of weld metals and base metal

4 Conclusions

- (1) The martensitic steel welded by DM-I weld metal contains reinforced phases, while both DM-II and DM-III alloys have little precipitates but mainly low carbon martensite formed during welding. In HAZ of the steel, different microstructure with martensite forms in welding, with coarse grains observed in the superheated zone. Compared with the weld and base metal, low hardness appears in the subcritically-quenched zone of the HAZ, but the impact toughness is higher than the base metal, meaning HAZ has weak cracking tendency during welding.
- (2) Compared with the initial state of the steel, the DM-I weld metal has the highest hardness and wear resistance but the lowest impact toughness, while the DM-III has somehow lowest hardness although the wear resistance is almost identical to the base metal. However, the mechanical properties of DM-II alloy are close to those of the base metal, showing a proper weldability as well as applicability for such cases.
- (3) Dimples are mainly found on the impact fracture of the weld metals, but impact fracture of both HAZ and base metal consists of both cleavage and dimples.

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