Welding Consumables for 780 MPa Class Steel with Excellent Notch Toughness after PWHT

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Abstract

Over the past few years, the demand for larger structures like spherical tanks and pressure vessels has risen, leading to a requirement for higher strength steel and welding consumables. However, the use of post-weld heat treatment (PWHT) to relieve welding residual stress has been known to deteriorate the notch toughness of high-strength weld metal. To investigate the factors contributing to this deterioration, an analysis has been conducted on the fracture surface morphology and microstructure after impact testing of weld metal for 780 MPa class steel, with electrodes for flux-cored arc welding as the main focus. The findings suggest that temper embrittlement and precipitation hardening caused by carbide are the main reasons for the deterioration of notch toughness after PWHT. Following several studies, an empirically derived component system of weld metal has been developed to minimize the negative aspects of temper embrittlement or precipitation hardening caused by carbide after PWHT. Utilizing these results, Kobe Steel has launched TRUSTARC™ [Note 1)] LB-80LSR as a shield-metal arc-welding consumable for 780 MPa class steel, which boasts excellent notch toughness even after PWHT.

Introduction

In the construction of spherical tanks, pressure vessels, and similar structures, PWHT is employed to reduce residual stresses introduced by welding and enhance fatigue properties. Due to the recent surge in energy demand, there is a trend toward upsizing and higher pressure in those structures, driving advancements in high-strength steel materials and welding consumables. More recently, significant progress has been made in the development of PWHT capable high-strength steel, exemplified by EN10028-6 P690QL2, boasting a tensile strength of 780 MPa, designed specifically for liquefied CO$_2$ tanks for ships[1)]. This advancement has resulted in an increased demand for welding consumables suitable for this type of steel.

Typical 780 MPa-class steel weld metal undergoes a decrease in notch toughness following PWHT. One contributing factor is temper embrittlement (mainly referring here to embrittlement caused by the segregation of phosphorus (P) at grain boundaries) occurring after specific PWHT[2)]. Another factor is precipitation hardening resulting from the formation and growth of carbides during PWHT due to impurity elements like Nb, V, and solid-solution hardening elements such as Cr, Mo[3), 4)].

This paper investigates the fracture morphology and microstructure of Charpy impact test specimens after PWHT, with weld metal produced using shielded metal arc welding rods (SMAW) and rutile-based flux-cored wire (FCW). Furthermore, the study explores the ingredient range of 780 MPa class steel weld metal, demonstrating excellent notch toughness even after PWHT.

1. Experimental method

Various components were integrated to manufacture the SMAW and FCW for 780 MPa class steel. **Table 1** outlines the composition range of the weld metals prototyped in this paper. Weld metals were created through prototype SMAW on a test plate with a thickness of 20 mm, a groove angle of 20°, and a root gap of 16 mm, employing direct current electrode positive (DCEP). Furthermore, weld metals were produced by prototype FCW on a similarly sized test plate through multi-layer welding using shield gas Ar+20%CO$_2$.

The average heat input during welding was 2.0 kJ/mm for SMAW and 1.3 kJ/mm for FCW. In SMAW, preheat and interpass temperatures were maintained at 95-105℃, while in FCW, the preheat temperature was set at 100-120℃, and the interpass temperature ranged from 140 to 160℃. To assess the effects of temper embrittlement and carbide-induced embrittlement, PWHT was conducted under two conditions: 2 hours at 580℃ and 8 hours at 620℃ after welding. Tensile test specimens and Charpy

Table 1 Chemical composition range of weld metals investigated in this study (mass%)

C	Si	Mn	Ni	Cr	Mo	Others
0.05 - 0.08	0.2 - 0.3	0.7 - 2.0	2.4 - 5.5	Max. 0.3	0.1 - 0.5	Ti, B

[Note 1)] TRUSTARC is a registered trademark (TM) of Kobe Steel.

impact test specimens were extracted from the central portion of the weld metals to evaluate their tensile strength and notch toughness. Additionally, the microstructure of each weld metal was observed using an optical microscope, scanning electron microscope (SEM), and scanning transmission electron microscope (STEM). The STEM observation samples were prepared using the extraction replica method. The identification of trace elements that segregate locally in the weld metal was performed using the three-dimensional atom probe tomography (APT) method.

2. Effects of PWHT on 780 MPa-class steel weld metals

The Larson-Miller parameter (hereinafter referred to as "LMP") serves as an index for PWHT conditions. LMP is calculated using Equation (1):

$$LMP = T(\log t + 20) \quad \cdots\cdots\cdots\cdots (1)$$

wherein, T represents the PWHT temperature (K), and t is the PWHT holding time (h).

A PWHT at 580℃ for 2 hours corresponds to an LMP of 17.3×10^3, and a PWHT at 620℃ for 8 hours corresponds to an LMP of 18.7×10^3. The relationship between the Larson-Miller Parameter (LMP) and -40℃ absorbed energy for conventional materials (SMAW and FCW) producing 780 MPa-class steel weld metals is depicted in **Fig. 1**. In terms of concentration in the weld metal, SMAW results in approximately 0.5% of Mo, while FCW yields around 2% of Mn.

SMAW exhibits reduced notch toughness as LMP increases. In FCW, notch toughness declines under low PWHT conditions when LMP ranges from 17.0 to 18.0×10^3. However, when LMP exceeds 18.0×10^3, notch toughness gradually recovers. The reduction in notch toughness after PWHT in SMAW is thought to result from both "temper embrittlement" and "embrittlement due to precipitation hardening caused by Mo-dominated carbides." The drop in notch toughness in FCW at LMP levels of 17.0 to 18.0×10^3 is primarily attributed to temper embrittlement. The factors contributing to the gradual recovery of notch toughness at LMP levels above 18.0×10^3 will be discussed later.

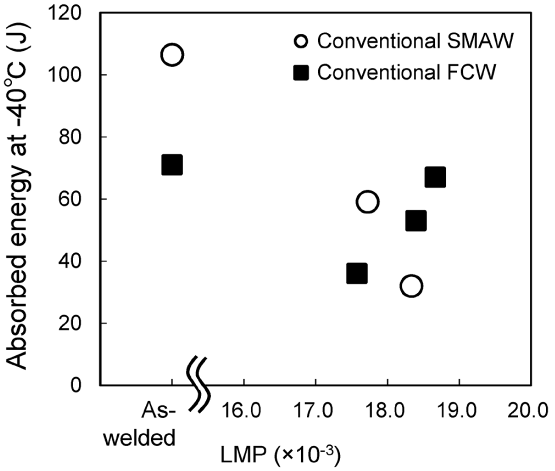

Fig. 1 Relationship between LMP and absorbed energy at -40℃ with conventional SMAW and FCW

2.1 Effect at low LMP conditions (LMP $\leqq 18.0\times10^3$) (Verification with FCW)

The investigation into the connection between low LMP conditions (PWHT at 580℃ for 2 hours, corresponding to LMP=17.3×10^3) and temper embrittlement was conducted using FCW within the composition range outlined in Table 1, with a specific focus on the Mn content in the weld metal. **Fig. 2** displays the fractography of -40℃ Charpy impact test specimens under low LMP conditions, showcasing variations in the Mn content in the weld metal. In such conditions, a higher Mn content in the weld metal leads to dominant grain boundary fracture along the prior austenite grain boundaries (PAGB), while a lower Mn content results in dominant ductile fracture.

In other words, it has been determined that the primary cause of temper embrittlement is grain boundary fracture along the PAGB, attributed to the Mn content in the weld metal. To explore elements cosegregating with Mn, trace elements around the PAGB in weld metals with varying Mn contents were measured using the APT method. The concentration profile of phosphorus (P), exhibiting local segregation, is depicted in **Fig. 3**. Phosphorus (P) segregates along the PAGB, and there is an observable trend of increased segregation with higher Mn content. Therefore, in weld metals with elevated Mn content, it is inferred that phosphorus (P) is more prone to cosegregation under low LMP conditions, thereby promoting grain boundary fracture.

2.2 Effect at high LMP conditions (LMP $> 18.0\times10^3$) (Verification with FCW)

In the composition range of weld metals outlined in Table 1, the study centers on weld metal with added chromium (Cr) and molybdenum (Mo) using FCW. Investigation has been carried out on the microstructure under high LMP conditions (8 hours of PWHT at 620℃, equivalent to LMP=18.7×10^3). The microstructure, examined with an optical

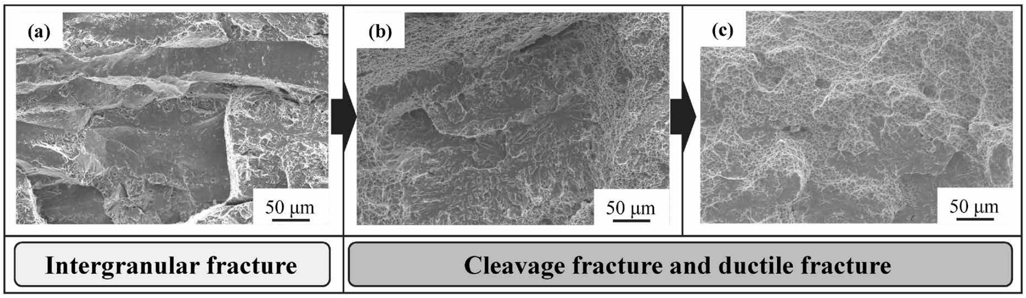

Fig. 2 Fractographs of impact test specimens containing different Mn content at low LMP condition
(a) High Mn content, (b) Middle Mn content, (c) Low Mn content

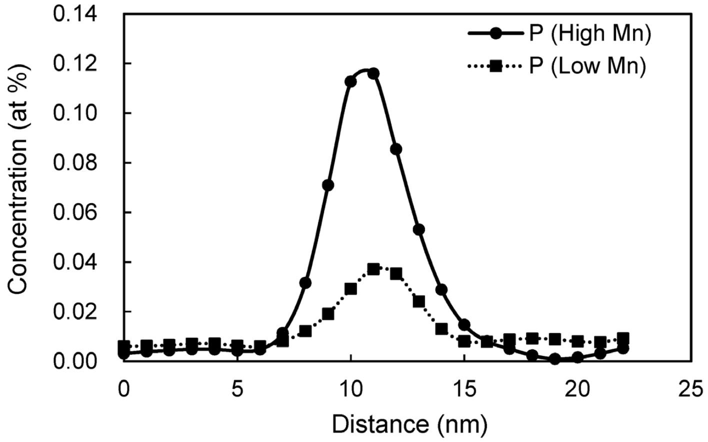

Fig. 3 Concentration profiles of phosphorus around the PAGB at low LMP condition measured by APT method

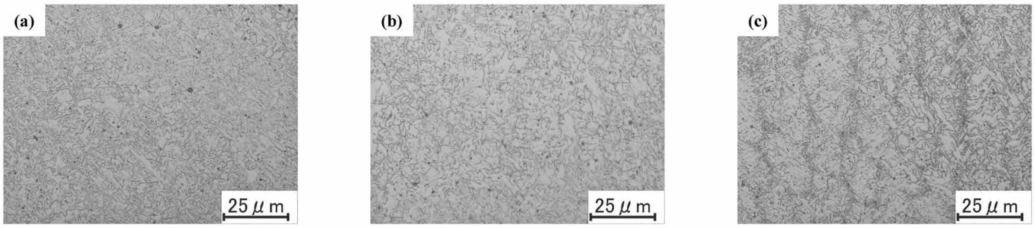

Fig. 4 Optical micrographs of weld metals (a) As-welded, (b) Low LMP condition, (c) High LMP condition

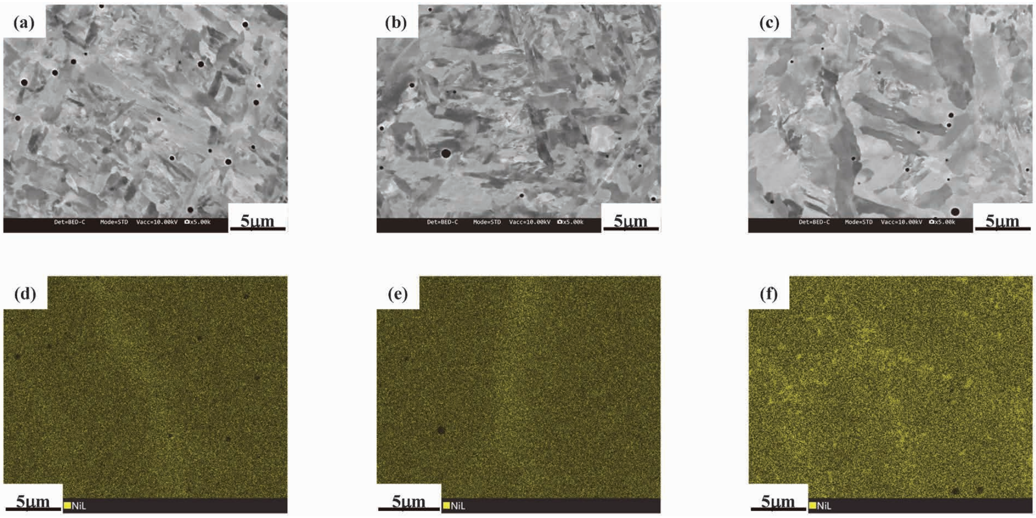

Fig. 5 SEM micrographs of weld metals and SEM-EDX analysis results of Ni
(a), (d) As-welded, (b), (d) Low LMP condition, (c), (f) High LMP condition

microscope, is depicted in **Fig. 4** in its as-welded state, with the inclusion of low LMP conditions. In the targeted weld metal, a mesh-like micro segregation zone (referred to as the "segregation zone") is observed under high LMP conditions, contrasting with the as-welded and low LMP conditions[5)].

Subsequently, in **Fig 5**, the microstructure near the segregation zone and the analytical results using a Scanning Electron Microscope with Energy Dispersive X-ray Analysis (SEM-EDX) are presented. Segregation zones were noted irrespective of PWHT, with a predominant concentration of Ni in the segregation zone. This hints at the potential for structural changes in the segregation zone after PWHT. Consequently, an analysis using electron backscatter diffraction (EBSD) was performed on the weld metal. The inverse pole figure (IPF) map and phase map obtained through EBSD are shown in **Fig. 6**. From the IPF map and phase map, it is apparent that the metallographic structure of the targeted weld metal is predominantly ferrite in the as-welded state, with PWHT causing the ferrite to coarsen. The microstructure referred to as "ferrite" here is a composite structure consisting of bainitic ferrite and in-grain ferrite (acicular ferrite)[6)].

Under high LMP conditions, an increase in austenite has been observed compared with the as-welded state. This austenite is identified as retained austenite, undergoing reverse transformation, and retained until room temperature in the high LMP conditions.

In the previously mentioned conventional material (FCW), the gradual recovery of notch toughness under high LMP conditions is believed to stem from the presence of soft austenite. The effective utilization of austenite retained through PWHT necessitates a reduction in the Ac1 transformation point, indicating the essential addition of a specific amount of alloy. Further validation is required for the alloying additive that manifests this effect.

In high LMP conditions, the possibility of embrittlement due to carbides was considered, leading to an investigation using STEM. The microstructure observed through STEM is shown in **Fig. 7**. The carbides found in the targeted weld metal are primarily composed of cementite,

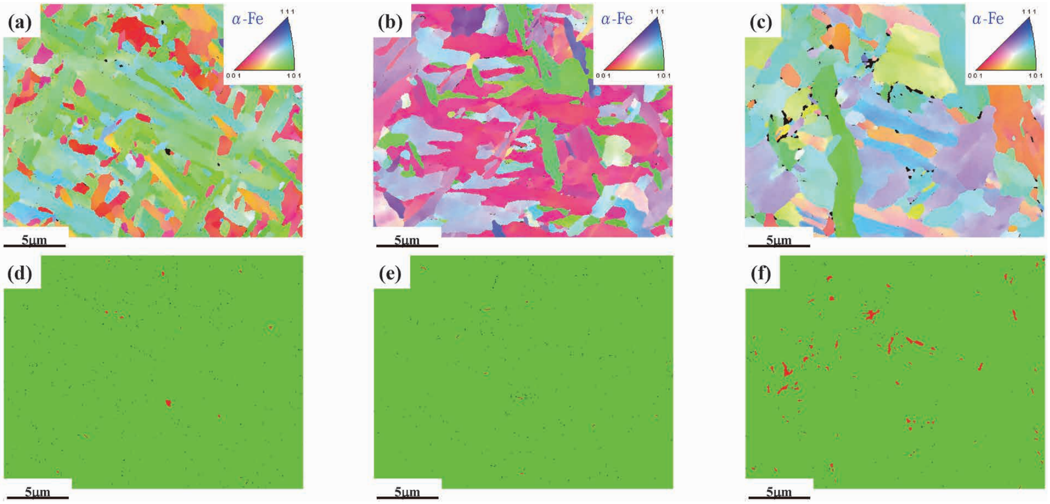

Fig. 6 IPF maps and phase maps obtained by EBSD
(a), (d) As-welded, (b), (e) Low LMP condition, (c), (f) High LMP condition (Green : Ferrite, Red : Austenite)

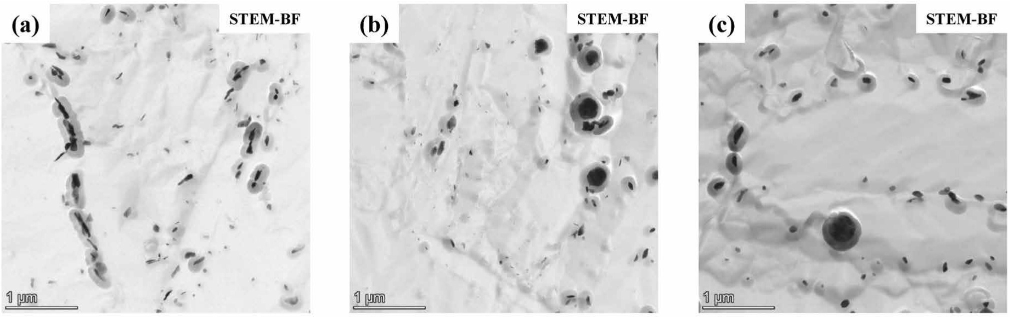

Fig. 7 STEM micrographs of weld metal (a) As-welded, (b) Low LMP condition, (c) High LMP condition

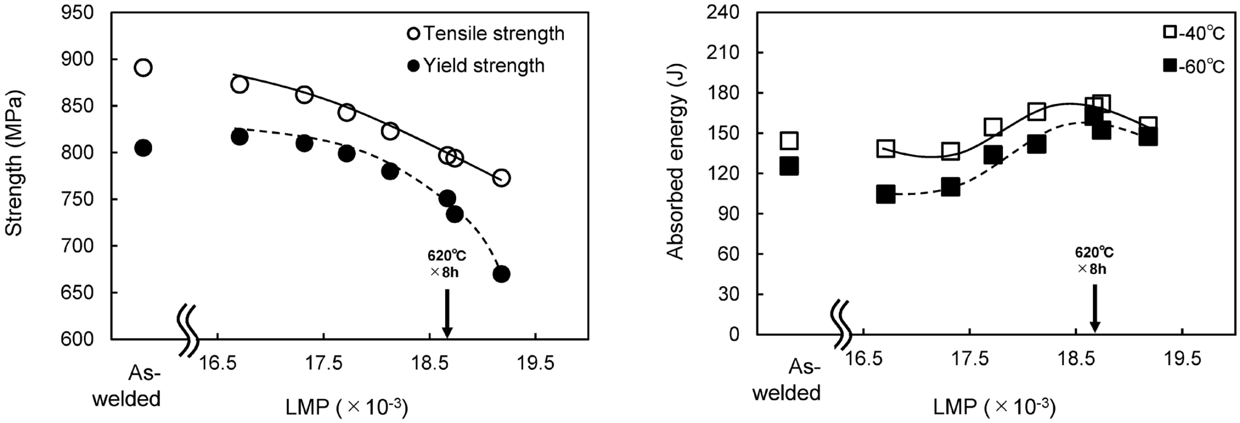

Fig. 8 Relationship between LMP and mechanical property of weld metals in this study

with only a small quantity of carbides other than cementite. Additionally, while some cementite exhibits Ostwald ripening tendencies after PWHT, generally, cementite in the range of 100 to 200 nm predominates. In weld metal where Cr and Mo have been adjusted, the formation and growth of carbides are suppressed, and embrittlement due to carbide-induced precipitation hardening is considered to be minor.

It should be noted that further investigation is necessary regarding these factors in the future.

2. Mechanical properties of the optimal composition system for weld metal

Within the composition range of the weld metal presented in Table 1, an investigation was conducted on the relationship between LMP and the mechanical properties of the weld metal. The shielding agent design for SMAW has been optimized to reduce oxygen levels, and the results are depicted in **Fig. 8**. The tensile strength of the weld metal meets or exceeds 780 MPa even under high LMP conditions. Moreover, regardless of the presence of PWHT, the absorbed energy at -40℃ consistently surpasses that of the conventional material. The embrittlement due to PWHT is minimal, allowing for responsive performance across a broad range of PWHT conditions. It is noteworthy that in SMAW weld metal, including the as-weld specimen, no grain boundary fractures are observed on the fracture surface of the Charpy impact test specimens after PWHT. SMAW for direct current electrode positive (DCEP) with excellent mechanical properties of weld metal of 780 MPa-class steel, has been commercialized as "TRUSTARC™ LB-80LSR."

Conclusions

A study has investigated the fracture morphology and microstructure of 780 MPa-class steel weld metal submitted to PWHT, with the aim of establishing design guidelines for achieving excellent notch toughness. The study found that adjusting the Mn content is effective in reducing temper embrittlement under low LMP conditions. Additionally, it identified the fact that adjusting the Cr and Mo content is effective in reducing embrittlement caused by precipitation hardening due to carbide formation/growth after PWHT. Furthermore, the insight was gained that optimizing other alloying additives contributes to the preservation of notch toughness after PWHT by facilitating the reverse transformation of austenite under high LMP conditions. On the basis of the insights gained, a shielded metal arc welding rod for 780 MPa-class steel, TRUSTARC™ LB-80LSR, has been developed, the rod exhibiting excellent notch toughness after PWHT. It is believed that this will contribute to expanding the possibilities of manufacturing in the future.

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