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CHARACTERISATION OF BALLISTICALLY TESTED ARMOUR STEEL JOINTS

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ABSTRACT

Armour-grade quenched and tempered (Q&T) steel is used for protection of military and non-military vehicles, because of its high energy-absorbing properties. Q&T steels used for armour applications require high strength, notch toughness, and hardness. The deformation and fracture behaviour of welded joints made from quenched and tempered steel closely conforming to AISI 4340 were investigated. The problems encountered in the past were reduced by depositing a soft austenitic stainless-steel buttering layer in between the BM and the hardfaced layer in the AHA joints(A-ASS filler, H – Hardfacing filler) . This study was planned to explore the insights of microstructural behaviour of AHF (A- ASS filler, H-Hardfacing filler, F- Low Hydrogen Ferritic filler). This article reports the changes observed in the microstructural features along the projectile trajectory in a multilayered armour steel joint AHF JOINT (A- ASS filler, F-LHF filler, H – Hardfacing filler) after ballistic testing.

Keywords: *Armour steel, Ballistic testing, Microstructure, Hardness*

1. Introduction

Armour-grade quenched and tempered (Q&T) steel is used for protection of military and non-military vehicles, because of its high energy-absorbing properties. Q&T steels used for armour applications require high strength, notch toughness, and hardness [1–3]. Most of the research carried out in the past on Q&T armour steel has concentrated on hydrogen-induced cracking (HIC) [4–6], heat-affected zone (HAZ) softening [7–9], ceramic front layer and metallic back layer composites, or fiber-encapsulated composites [10]. It was recently reported that the presence of an austenitic stainless-steel (SS) buttering layer between the armour plate [base metal (BM)] and weld metal/hardfaced metal resulted in enhanced ballistic performance and successfully held the weld layers intact when a projectile was fired at interfaces and the heat-affected zone (HAZ) [11]. It was also reported that the ballistic performance of the weld metal is enhanced, resulting in shattering of the projectile [12]. High-strain-rate fracture and failure of high-strength low-alloy steel in compression were investigated by Odeshi et al. [13]. It was observed that thermal softening as a result of adiabatic heating in the materials controls the deformation and fracture behaviour. The role of retained austenite, twinned plate martensite interfaces, and grain boundaries in determining the ballistic performance of steel was explored by Maweja and Stumpf [14]. The effect of the aluminium alloys after impact loading by a kinetic energy projectile were investigated by Milman et al. [16]. Murret al. [17] explored the novel deformation processes, microstructures involving ballistic penetrator formation, hypervelocity impact, and penetration phenomena using light and transmission electron microscopy. From this literature review, it is apparent that the reported work on the microstructural characteristics of ballistic tested weld metal region is very scant. The microstructural features of ballistic tested armour steel welds (before and after ballistic testing) of AHA joints were reported by Balakrishnan et al. [12]. This investigation aims to evaluate the microstructural features of the ballistically tested armour steel AHF joints in continuation of study reported by Balakrishnan et al. This article reports the changes observed in the microstructural features along the projectile trajectory in a multilayered armour steel joint after ballistic testing.

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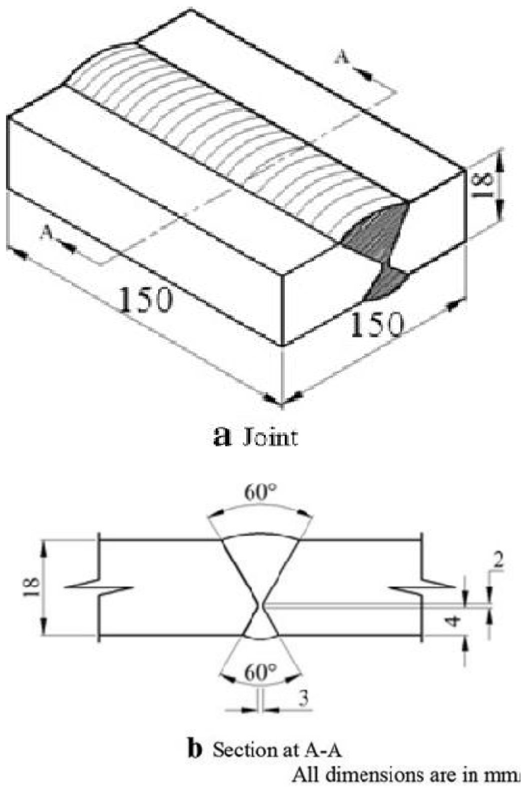


Fig.1 Joint configuration

2. Experimental Work

The BM used in this study was 18-mm-thick high-strength, low-alloy Q&T steel closely conforming to the AISI 4340 specification. Heat treatment applied to the BM consisted of austenizing at 900^0C followed by oil quenching and subsequent tempering at 250^0C. This heat treatment yields high hardness and strength, and good toughness for this BM. The chemical compositions of BM and filler metal are presented in Table 1. In this investigation, an unequal double V-joint configuration was prepared as shown in Fig. 1. The bevelled edges were buttered with SS electrodes and hardfaced with 5.5-mm-thick chromium carbide; the result was a hardfaced interlayer between SS root and LHF capping weld layers which are shown in fig.2. The specifics of the buttering procedure are discussed elsewhere [11, 12]. The shielded metal arc welding (SMAW) process was selected because it is commonly employed in the fabrication of combat vehicles [18]. The SS electrode was selected because it avoids the time-delayed cracking tendency of Q&T steel weldments [3]. The preheating and inter pass temperatures were maintained at 150^0C during welding. The fabricated target was subjected to standard ballistic testing, and its performance was compared with that of the armour-grade Q&T steel BM.

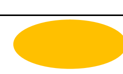
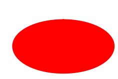
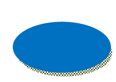
The ballistic test procedure was discussed in previous publications [2, 7, 8, 10–12]. Four shots were fired into the welded target plate to evaluate its ballistic performance. The depth of penetration (DOP) of the projectile into the target plate was the metric used for evaluating ballistic performance. The weldment was characterized by microstructural analysis and hardness measurements.

Etchants used included 2 % Nital for BM and HAZ region, aqua regia for the SS welds metal region, and Villella's reagent for the hardfaced region. After ballistic carefully extracted in the through-thickness direction for analysis via light microscopy. Hardness measurements were carried out as per the ASTM E-384-11 standard [19] before and after ballistic testing. A Vickers micro hardness testing machine was employed to measure the hardness along the weld center line (WCL) and across the WCL with 50g load for dwell time of 15 s.

Table 1 Chemical composition (wt.%) of base metal and all weld metal deposits

ELEMENT	C	Mn	Si	S	P	Cr	Ni	Mo	V	Fe
BASE METAL AISI 4340	0.35	0.54	-	-	-	1.25	1.75	0.52	-	Bal
ASS ELECTRODE	0.08	3.3	0.90	0.015	0.04	20.30	8.50	1.5	-	Bal
AWS E307										
HARDFACING ALLOY	4.0	1.0	1.50	-	-	30.00	-	2.0	0.50	Bal
AWS E FeCr-A7										
LHF ELECTRODE AWS E11018-M	0.050	1.30	0.242	0.014	0.020	0.133	2.12	0.222	-	Bal

Table 2 Illustration of weld beads

S.no		CONSUMABLES	OPERATIONS
1		E 307-16	ASS- Root
2		E FeCr-A7	HARD FACING
3		E11018-M	LHF- Capping

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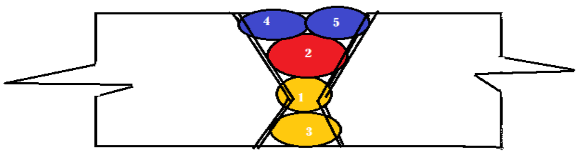

Fig.2 Scheme of welding (AHF joint)

3. Results

3.1 Microstructure

The macrostructure of the joint is presented in Fig.3. Macrostructures reveal that there is a clear bonding between each layer and the buttering layer, and also no interfacial cracks in between layers or hardfacing. Similarly, there is no crack at the interface between the weld and base metal due to the presence of soft ASS buttering layer.

Microstructure of the joints was examined at different locations and optical micrographs taken at different regions of welded joints are displayed in Fig.5.The microstructure of base metal consists of acicular martensite structure with fine needles of lath martensite as shown in Fig. 5.a. The microstructures of various locations are shown in Figs. 5.b to 5.h. The hardfaced region of both ASS and LHF capping weld consisting the microstructure of homogeneous cast like structure shown in Fig. 5.b. It is composed of hard phase precipitates (Carbides) of hexagonal chromium carbides of different sizes on softer austenitic matrix. Large spine like carbides are clearly visible in the microstructure on both sides of the hardfaced layers on AHF the joints. The weld interface region of ASS buttering and base metal reveals that fine anchoring was obtained due to the formation of continuous epitaxial growth as shown in Fig. 5.c. The weld interface region of ASS buttering and hardfacing also reveals that fine continuous epitaxial growth of austenitic matrix and hexagonal carbides as shown in Fig. 5.d. The weld interface region of hardfacing and ASS capping reveals that epitaxial growth of δ ferrite in austenitic matrix as shown in Fig. 5.e. The weld interface region of hardfacing and LHF capping reveals that fine acicular ferrite in matrix as shown in Fig. 5.f.

The undiluted weld metal microstructure in ASS root and ASS capping consisting of grain boundary δ ferrite in a plain austenitic matrix as shown in Fig. 5.g. The undiluted weld metal microstructure in LHF capping consisting the acicular martensitic structure of grain boundary δ ferrite in a plain austenitic matrix as shown in Fig. 5.h.

The interfaces between buttering and base metal and buttering and hardfacing have similar morphology for both the joints (AHA and AHF). Interface microstructure of sandwiched joints has smaller portion of unmixed zone near to the periphery of the fusion boundary along with a softened layer of untempered martensite stucture as shown in Fig.5.3d.

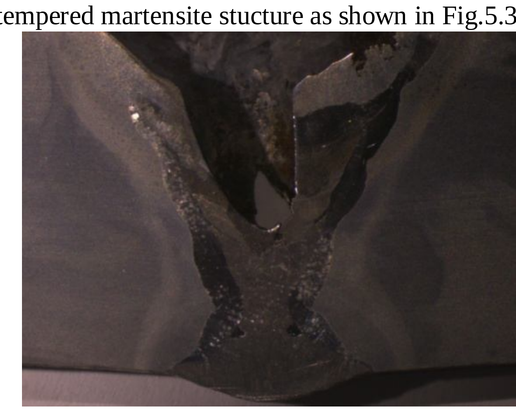

Fig. 3.1 Weld specimen

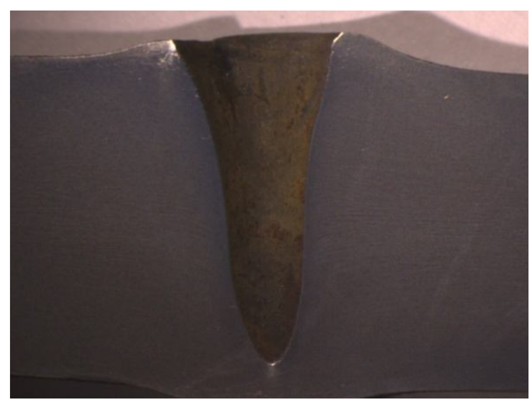

Fig. 3.2 Parent metal

Fig.3 Macrograph of the bullet trajectory

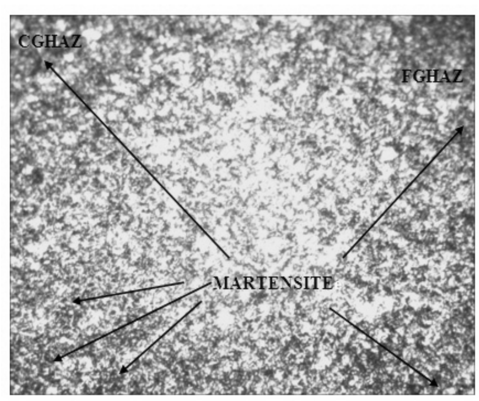

Fig.4 Microstructure of HAZ region

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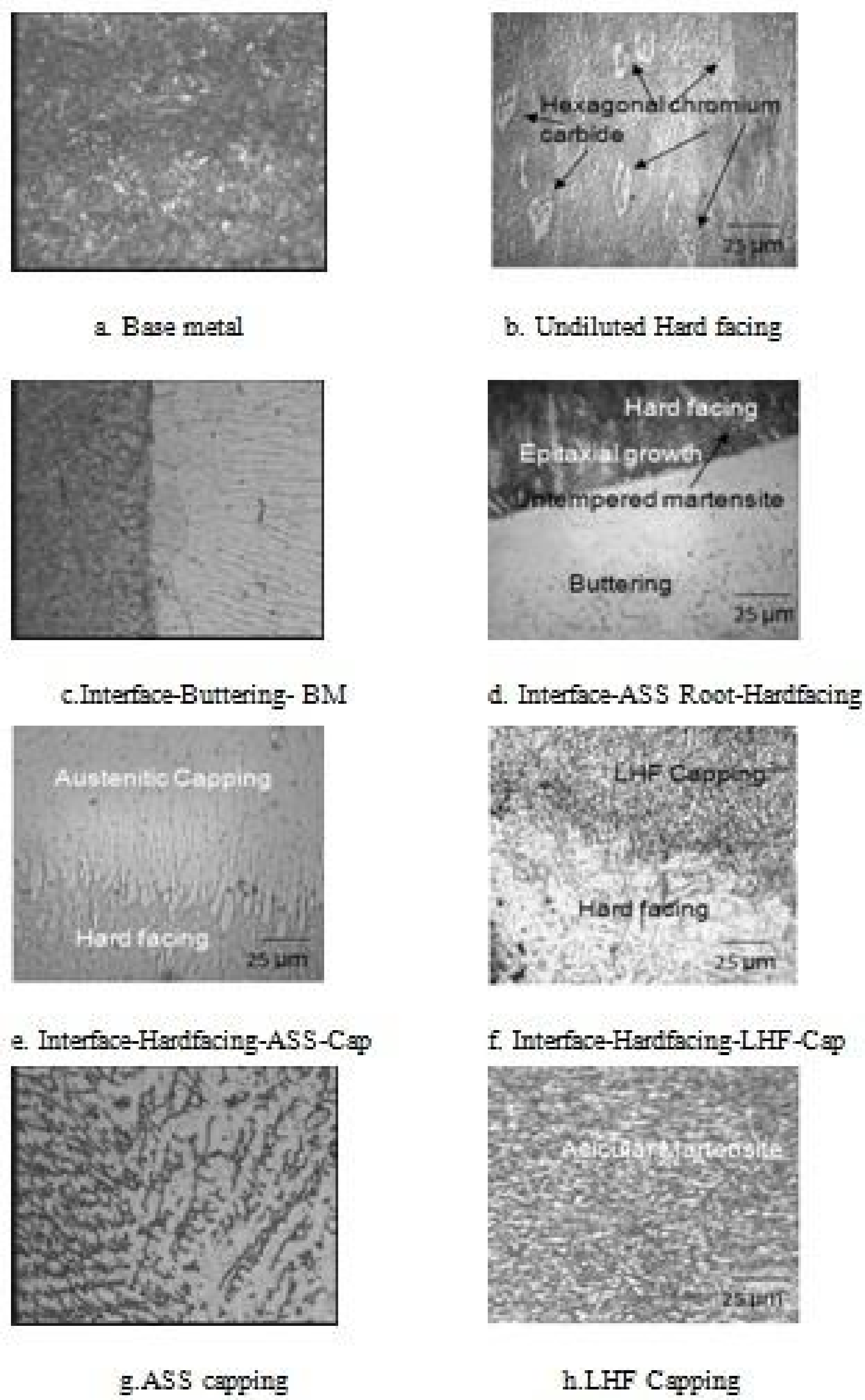

Fig.5 Microstructure of base metal and welded joints at various locations

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The HAZ invariably has the same microstructure in each combination both AHA and AHF as shown in Fig.4. The microstructure clearly depicts the presence of coarse martensite nearby the fusion line towards the base metal side and uniformly distributed martensite.

3.2 Hardness

The hardness measurement was carried out in two different directions to evaluate the hardness disparity both along and across the weld cross section. More than fifteen readings were taken at close proximity From the hardness measurement results, the high hardness is achieved in hardfaced layer is due to the presence of chromium carbide and the lower hardness is at the ASS weld layer. From the fig.6 results, it is clear that the interface hardness values have some wide range values. This could be attributed to SMAW process characteristic feature of having around 25-30 % dilution effect. This is clearly revealed in the hardness measurement at the interfaces of the layer and interface between weld layer and base metal.

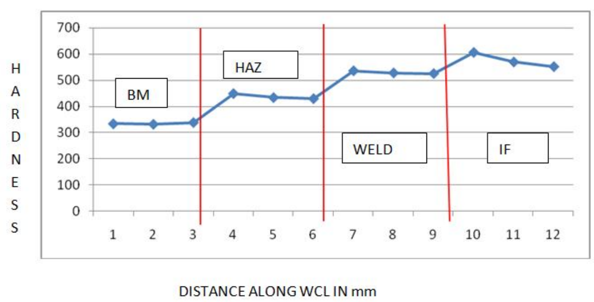

Fig.6 Micro hardness profile for various locations for AHF joint

3.4 Ballistic performance

In AHF combinations, ferritic weld metal on the top front layer, the microstructure consisting fine acicular ferrite is known to be very beneficial in reducing the tendency for cracking or fissuring in weld metals. The ferrite is helpful when the welds are restrained, the joints are large, and when cracks or fissures adversely affect service performance. This combination of joint also serves the same way to reduce the velocity of the impact and finally stop the projectile. The maximum benefit of reducing the velocity of the projectile is achieved by the hardfaced interlayer in the joint, but at the same time the thickness of the hardfaced layer play a vital role towards the ballistic performance.

There is a steep increase in hardness was observed in the interface between hardfacing and LHF capping in AHF joint. This sudden increase in hardness is due to the interface microstructure, which is comprised of epitaxial growth of elongated constituents of ferrite.. In the LHF capping, the structure changes from hexagonal chromium carbide in an austenitic matrix to acicular ferrite and in ASS capping, a change of hexagonal chromium carbide to δ ferrite in a plain austenitic matrix. The acicular morphology of ferrite structure enhances the hardness and toughness in the LHF weld metal.

A good combination of strength and toughness of low alloy steel weld is achieved by so called acicular ferrite microstructure, consisting of small inter weaving ferrite plates formed within the austenite grains. The combination of high strength and toughness is attributed to the plates of acicular ferrite nucleate intergranularly on non-metallic inclusions while maintaining an orientation relationship with the austenite. Acicular ferrite is formed as a direct nucleation from the inclusions resulting in randomly oriented short needles with fine grain size and hence the high hardness and strength. The effect of dilution reduces the interface hardness. Compared with ASS capping LHF capping combination holds well when subjected to ballistic test because it is able to hold more amount of capping layer from the removal of layer from the weld joint when the projectile passing through the joint. This gives an indication the LHF capping is superior when compared with ASS capping.

4. Conclusion

An attempt was made to exemplify the microstructural transformations that occur in ballistically tested multilayered armour steel joint. Results show that:

1.The hard layer containing chromium carbide absorbs the ballistic impact energy by forming high cracks.

2.The combination of hard and soft layers improved the ballistic immunity of the joint by absorbing impact energy (due to cracking of primary carbides) and controlling the projectile travelling direction as vertical due to the presence of the soft backing layer by way of possible reduction of projectile velocity coupled with crack blunting behaviour.

3.The buttering layer enhances ballistic immunity by the resultant

microstructure and hardness distribution and successfully keeps the weld layers intact when the projectile is fired at the WCL, interfaces, and HAZ.

4.At the WCL, further investigation is required for analytical correlation of the projectile shattering

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mechanism and resulting hardness distribution, because this study correlated the ballistic test results with the resultant microstructure and micro hardness values.

5.Further investigation is needed to improve the ballistic performance of the armour steel against the multi shot projectiles.

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