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Development and design of microstructure based coated electrode for ballistic performance of shielded metal arc welded armour steel joints

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Joining of high strength armour steel plate developed for lighter armour vehicles using both austenitic and ferritic type of electrode/filler wire could show inferior ballistic performance of the welds. Combination of hard facing electrode and softer Austenitic Stainless Steel electrodes, though provided improved ballistic performance, might not satisfy main design criteria such as strength and toughness due to non-homogeneous microstructure of weld metal. In order to satisfy improved ballistic performance as well as other design parameters, it is highly desirable to develop coated electrode which will attribute more homogeneous microstructure in weld metal similar to high strength armour steel plate.

The present investigation has attempted to obtain martensite, bainite and some amount of retained austenite in the weld metal by proper design of alloying elements in the coating of SMAW electrode based on metallurgical index. Three different electrodes attributing different combination of microstructural constituents in armour steel weld metals exhibited excellent ballistic performance combined with other design criteria such as strength and toughness at −40°C. However, among the different microstructural constituents lower bainite along with retained austenite showing maximum toughness both at room temperature and at −40°C could be considered as most desirable microstructure in armour steel weld metal.

1. Introduction

Armour grade quenched and tempered (Q & T) steel closely confirming to AISI 4340 is primarily used for highly stressed structures in many critical defence applications and non-military vehicles such as the construction of the hull and turret of combat vehicles and provides several potential advantages including their superior ballistic performance [1,2] lower weight, and manufacturing costs, ease of handling and transport etc. Furthermore, these highly mobile, metallic structures must be resistant to cracking, spalling and fracture upon multiple impacts from a wide range of projectiles selected for each class of vehicle from the full range of antitank weapons available today [3]. Thus ballistic performance which is defined as the maximum resistance against projectile penetration [4,5] is the most important criteria for armour grade Q& T steel. It is generally considered that the harder the steel, the better is the resistance to penetration [6]. Recent work by Maweja and Stumpf [7,8] on armour steel plate has shown that neither a higher hardness nor higher mechanical properties (Yield strength, ultimate tensile strength, impact energy, and % elongation) appears to be exclusive or even reliable criteria for predicting the ballistic performance. Alternatively, the microstructure based design has the advantage of addressing a direct relationship between the microstructure and ballistic performance. Predominantly twinned plate martensite with retained austenite was found superior in ballistic performance [7]. The percentage of retained austenite typically between 1% and 7% mainly governs the resistance to localised yielding of the armour steels and thus improves ballistic performance [5].

Shielded metal arc welding (SMAW) and flux cored arc welding (FCAW) processes are widely used in the fabrication of combat vehicles [9]. The microstructural features in the weld and heat-affected zone (HAZ) have been shown to have a drastic influence on the ballistic performance of the joints. Several studies [10] were attempted to evaluate ballistic performance of the armour steel joints using different types of electrodes. For example, both austenitic and ferritic type of electrode/filler wire were attempted with varying heat input and weld joint only with lower heat input showed good ballistic performance. On the other hand, the weld joint with higher heat input having wider soft zone attributed inferior ballistic properties [10]. Again, for improved ballistic performance of armour steel plate joints, different weld procedure

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Table 1
Composition of flux ingredients used for coating.

Sl. No	Flux ingredient	Weight %		
		E1	E2	E3
1	FeTi powder	4.72	3.80	3.80
2	FeMn (HC) powder	4.72	6.75	6.75
3	FeCr (HC) powder	4.72	6.75	6.75
4	Fe-powder	1.88	1	1
5	Rutile powder	3.77	4.80	4.80
6	$CaCo_3$ powder	26.65	27	27
7	Fluorspar powder	21.95	22	22
8	Ni-powder	11.35	10	9.5
9	Mo-powder	1.35	2.2	2.2
10	FeSi powder	7.55	5.75	5.75
11	White TiO_2 powder	1.88	2	2
12	Feldspar powder	7.56	5.75	5.75
13	Graphite powder	–	0.2	0.7
	Extruding agent			
14	Na-alginate Powder	1.5	1.5	1.5
15	CMC Powder	0.5	0.5	0.5
	Binding agent			
16	K-silicate	14	14	14
17	Na-silicate	4	4	4

using different combination of coated electrodes for a given joint were attempted [11]. In one such a joint, three different types of coated electrodes such as austenitic stainless steel (ASS) electrode for capping front layer, chromium carbide hardfacing electrode as interlayer and the ASS electrode for root layer were used and other joint was made with similar layers except low hydrogen ferritic (LHF) electrode as capping front layer. It was reported that in both the joints projectile was stopped totally by high hardness hard facing interlayer. However, between two different types of joints authors reported that LHF electrode for capping front layer provided better ballistic performance than ASS for capping front layer. This is mainly due to presence of acicular ferrite with bainitic structure. Similar investigation using different types of hardfacing electrodes such as chromium rich carbide and tungsten carbide were performed by M. Balakrishnan et al. [12] and S. Babu et al. [13] improved ballistic performance was reported. Although the previous work showed improved ballistic performance of the joints by introducing harder hardface deposit layer in between soft ASS layer, the yield and ultimate strength, % elongation at room temperature and transverse Charpy impact energy at −40 °C, which are the main design parameters for most armour steel plates [4], have not been evaluated. Thus it is highly probable that previous approach of improving ballistic performance of weld metal with non-homogeneous microstructure containing harder constituents may not satisfy other design criteria. In order to satisfy the other design parameters as well as improved ballistic performance, it is highly desirable to develop coated electrode with more homogeneous microstructure such as martensite, bainite and retained austenite in the weld metal.

It is to be mentioned here that formation of twinned martensite with retained austenite, which showed improved ballistic performance in high strength armour steel, is commonly associated with higher carbon content along with other alloying elements [14]. But, the conditions prevailing in making steel (armour steel plate) and producing weld metal differ significantly. In making steel, close control of composition, removal of undesirable elements such as sulpher and phosporous and control of cooling rate after thermo-mechanical treatment are possible and hence it is relatively easier to obtain desired microstructure. But in case of weld metal, close control of composition, refinement, mechanical working and accurate control of cooling rate cannot be performed. Furthermore, weld metal with relatively higher carbon content (0.25 wt% C) and segregation of alloying elements encountered during the solidification leads to cracking [15–17]. This imposes constraint on the enrichment of alloying elements, particularly the carbon content and thus the electrodes are being produced by trial and error method based on the conceptual knowledge on alloy design.

Although recent studies on improved performance of armour steel plate have opened up an arena regarding a number of critical issues, but it appears that hardly any published work attempted to develop a coated electrode exclusively based on microstructural based design to improve the ballistic performance of weld metal along with fulfillment of other design criteria of high strength armour steel plate.

The main focus of the present work is to develop SMAW electrode with a systematic variation of alloying elements through coating composition of the electrode for achieving the target composition of high strength armour steel plate [4]. Then the butt welded joints of high strength armour steel plate was produced by the developed electrodes and the performance of the welds has been evaluated using ballistic testing, tensile testing, impact toughness at room temperature and at −40 °C. Finally the microstructures have been exclusively characterized by OM (optical microscopy), SEM (scanning electron microscope), TEM (transmission electron microscope) with SAD (selected area diffraction) pattern and XRD (X-ray diffraction) and correlated with mechanical properties and ballistic performance of the weld metals.

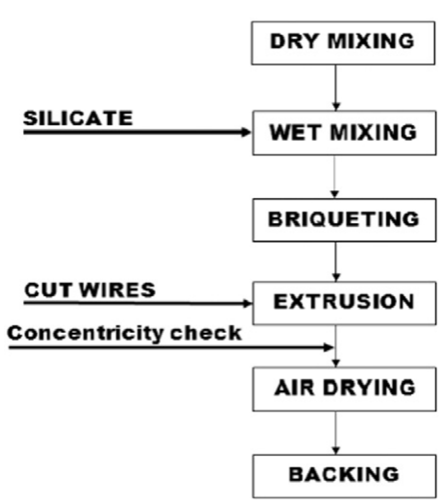

Fig. 1. Flow process chart for electrode extrusion.

2. Experimental procedure

An experimental electrode formulation was made by varying the flux ingredients systematically in the coating to achieve the target composition (0.37–0.43 wt% C, 0.5–1.8 wt% Mn, 0.6–1.2 wt% Si, 0.8–1.5 wt% Cr, 0.5–0.6 wt% Mo and 1.8–4.0 wt% Ni) [4]. The flux ingredients used in the experiment is given in Table 1. Careful considerations have been made for each change that would have an influence on the metallurgical properties of the resultant weld metal in the form of chemical composition and microstructure.

The constituents of the coating were first weighed in various proportions according to the weight requirements of the selected composition. The extrusion process has been illustrated by the flow chart shown in

Table 2
Chemical composition of base metal (wt%).

Element	C	Mn	Si	S	P	Cr	Ni	Mo	Fe
Base metal (AISI 4340)	0.29	0.49	0.22	0.007	0.007	1.43	1.58	0.40	Bal.