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# Metallurgical characteristics of armour steel welded joints used for combat vehicle construction

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Austenitic stainless steel (ASS) and High nickel steel (HNS) welding consumables are being used for welding Q&T steels, as they have higher solubility for hydrogen in austenitic phase, to avoid hydrogen induced cracking (HIC) but they are very expensive. In recent years, the developments of low hydrogen ferritic steel (LHF) consumables that contain no hygroscopic compounds are utilized for welding Q&T steels. Heat affected zone (HAZ) softening is another critical issue during welding of armour grade Q&T steels and it depends on the welding process employed and the weld thermal cycle. In this investigation an attempt has been made to study the influence of welding consumables and welding processes on metallurgical characteristics of armour grade Q&T steel joints by various metallurgical characterization procedures. Shielded metal arc welding (SMAW) and flux cored arc welding (FCAW) processes were used for making welds using ASS, LHF and HNS welding consumables. The joints fabricated by using LHF consumables offered lower degree of HAZ softening and there is no evidence of HIC in the joints fabricated using LHF consumables.



## 1. Introduction

In recent years, there has been an increasing need for Q&T steels for use in highly-stressed structures, including many critical applications in defence such as construction of the hull and turret of combat vehicles. The major objective of any armour design and development is that to ensure superior ballistic performance. The ballistic performance of various armour steels is characterized based on their hardness. Generally, the harder the steel the better is the ballistic performance, hence high-hardness steels are used typically where penetration resistance and weight reduction are key consideration, low-hardness type steels being used where shock resistance is important in military applications [1]. The performance of steels depends on the properties associated with their microstructures, that is, on the crystallographic arrangements, volume fractions, sizes, and morphologies of the various phases constituting a macroscopic section of steel with a given composition in a given processed condition. Steel microstructures are made up of various phases, sometimes as many as three or four different types, which are physically blended by solidification, solid-state phase changes, hot deformation, cold deformation, and heat treatment. Each type of microstructure and product is developed to characteristic property ranges by specific processing routes that control and exploit microstructural changes [2]. The ballistic requirement of Q&T steels used for armour applications calls for high strength, greater notch toughness and moderate hardness. These low alloy steels are essentially nickel-chromium-molybdenum type and all the above properties are best obtained in fine (acicular) tempered martensitic structures produced by quenching and tempering heat treatments [3].

### 1.1. Armour grade Q&T steel welds

Q&T steels with yield strength upto 1500 MPa and having carbon equivalent in the rage 0.7–0.9 are generally used for the fabrication of combat vehicles which require resistance against projectile penetration. Welding is the major fabrication route

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adopted in armour vehicle fabrication. Hydrogen induced cold cracking after welding in HAZ and HAZ softening due to weld thermal cycle are two major problems that need to be addressed during welding of armour grade Q&T steels as they hinder the ballistic performance when they are used in armour applications [4].

### 1.2. Cracking in armour grade Q&T steel welds

Two types of cracking are expected to occur in the HAZ of armour grade Q&T steels. They are cracking at high temperature due to low ductility of HAZ and the second type of cracking which occurs at low temperature after a delay of time. The cracking that occurs at low temperature can be either due to hydrogen embrittlement or restraint cracking [5]. Solution to overcome HIC are preheating and precautions during welding such as baking of electrodes and use of consumables which form austenitic phase. One of the main causes of hydrogen induced cracking is high hardness in the HAZ. For this reason, to maintain HAZ hardness below the cracking susceptible region, preheating is recommended [6]. Inspite of taking all these precautions HAZ cracking is reported to prevail in the high hardness (470–550 Hv) condition of the base metal. Softening in the HAZ of the weldments of Q&T steel occurs due to the weld thermal cycle and is a characteristic of the welding process and consumables used in fabrication. The presence of a soft zone in welded structure may limit the design strength to a lower value and may also influence the ballistic behaviour of weldments [7].

### 1.3. Welding consumables and processes adopted for armour grade Q&T steels

Austenitic stainless steel (ASS) welding consumables and high nickel steel (HNS) consumables are being used for welding Q&T steels, as they have higher solubility for hydrogen in austenitic phase, to avoid hydrogen induced cracking (HIC). These consumables find application for the welding of high hardness Q&T steels to meet the service requirements of armoured vehicles. But use of ASS and HNS consumables for a non-stainless steel base metal must be avoided as they are more expensive. In recent years, the development of low hydrogen ferritic steel (LHF) consumables with basic coatings that contain no hygroscopic compounds are attempted for welding Q&T steels [8–10] which are less expensive than the ASS and HNS consumables.

The majority of armour fabrication is performed by fusion welding process and they demand for the highest welding quality. Shielded metal arc welding (SMAW) and the flux cored arc welding (FCAW) processes are widely used in fabrication of combat vehicle construction [11]. The welding consumables and processes have a substantial influence on hydrogen induced cracking and heat affected zone softening in armour grade Q&T steels. Armour grade Q&T steel has well established weld compatibility with ASS and HNS consumables and they are used in construction of armour vehicles. Thus, there is a need to utilize LHF consumables for welding armour grade Q&T steel used in construction of military vehicles. The use of LHF consumables may reduce heat affected zone softening and may offer equal resistance to HIC as that of ASS and HNS consumables. From the above discussion, it is anticipated that welding consumables and welding processes may have considerable effect on the performance of the armour grade Q&T steel joints metallurgical. The properties and integrity of the weld metal depend on the variant microstructural features in the various zones of the joint [12,13]. The use of ASS, HNS and LHF consumables for welding armour grade Q&T steel by SMAW and FCAW processes will lead to the formation of distinct microstructural features in the weld and heat affected zone and will have a significant influence on the performance of the joints. Hence, in this investigation, an attempt has been made to study the effect of welding consumables (ASS and LHF) and welding processes (SMAW and FCAW) on metallurgical characteristics of armour grade Q&T steel weldments. The aim of this investigation is to assess the feasibility of using LHF consumables for fabrication of armour grade Q&T steels and its metallurgical compatibility with the base metal.

## 2. Experimental work

### 2.1. Base material

The base metal used in this investigation is typically a low alloy quenched and tempered steel used in the construction of combat vehicle construction. The heat treatment of the base metal used in this investigation comprises of austenitising at 900 °C followed by oil quenching and subsequent tempering at 250 °C. This combination of heat treatment is responsible for high hardness, higher strength and toughness and hence it imparts superior resistance against any ballistic attack and they are used in the construction of military vehicles [14,15]. The base metal used in this investigation is armour grade quenched and tempered steel closely confirming to AISI 4340 specifications.

### 2.2. Filler materials for joining

The filler metals used in this investigation confirming to the following specifications as given below:

1) Basic coated ASS electrode for SMAW process closely confirming to AWS E 307 specifications with Cr and Ni as main alloying elements
2) Basic coated LHF steel electrode for SMAW process confirming to AWS E 11018-M 307. It is a typically low alloy ferritic electrode.
3) Basic coated HNS steel electrode for SMAW process confirming to AWS E $NiCrFe_3$ with greater proportion of nickel content along with chromium and manganese.
4) Basic coated ASS flux cored wire for open arc FCAW process closely confirming to AWS E 307 T1-1 specifications with Cr and Ni as main alloying elements.
5) Basic coated LHF steel flux cored wire for FCAW process with $Co_2$ shielding confirming to AWS E 110 T5-K4. It is a typically low alloy ferritic steel flux cored wire.

The chemical composition of the base metal and filler materials are presented in Table 1.

### 2.3. Fabrication of single ‘V’ butt joints

Rolled plates of 14 mm thick base metal were sliced into the required dimensions (300 mm × 100 mm) by abrasive cutters and grinding. Single ‘V’ butt joint configuration, as shown in Fig. 1 was prepared to fabricate the joints using ASS, LHF and HNS consumables by SMAW and FCAW processes. A preheating temperature of 100°C was used in this investigation as per the guidelines cited elsewhere in the literature [15-17]. In order to ensure complete side wall fusion, the welding assembly was placed at 25 to 30° inclined to the work table surface. About 4 to 5 passes were deposited to complete the welding and deposited slag was completely removed between passes. A temperature of 150°C was maintained between subsequent passes in accordance with guidelines cited elsewhere [5]. The direction of welding was parallel to the rolling direction. All necessary care was taken to avoid

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