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Mechanical properties and microstructures of steel panels for laminated composites in armoured vehicles

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ABSTRACT

This paper present the study about the mechanical properties of two high strength low alloy steels for replacing the current rolled homogeneous armour (RHA) for ballistic application. High strength low alloy steel has been widely adapted as a ballistic plate in light armoured vehicle. However, the current used RHA plate is very heavy thus restricted the manoeuvrability of the armoured vehicle. The aim of this study is to find materials suitable to be used for production of composite protection panel which is lighter yet has similar mechanical properties to RHA. The tensile strength and hardness of AISI 4340 and AR500 steels were evaluated and compared to that of RHA and the results were analysed based on its chemical compositions and microstructural observation. Values of these properties are primarily reflected by its microstructures and chemical compositions. Therefore, microscopic observation of microstructural arrangement and phases are essential in understanding the hardness and stress-strain behaviour of these metals. Results indicate similar tensile properties were observed in RHA and AR500 but different properties obtained for AISI 4340. Tensile strength of RHA and AR500 were 1750 MPa and 1740 MPa respectively followed by AISI 4340 at 1020 MPa. AISI 4340 steel exhibited the highest elongation at 20.6% compared to RHA and AR500 at 13.3 and 12.5%, respectively. Higher degree of carbon content in fine martensitic structure of RHA and AR500 led to high hardness. Imperfections in RHA and AR500 were also removed by hot rolling process as indicated by white banding that cause higher in tensile strength. Retained austenite and coarse microstructure of AISI 4340 steel contributed to higher ductility compared to AR500 and RHA. Therefore the tensile properties of RHA and AR500 were found similar due to its microstructure behaviour. This similarity allows AR500 to be utilised as alternatives to RHA in armour plate application.

Keywords: High strength steel; tensile strength; ductility; hardness; martensitic.

INTRODUCTION

Various materials especially metals, ceramics, polymers, and composites have been utilised in light vehicle defence technology. With each material appearing significant in respective applications, metals are mostly utilised for ballistic protection due to its mechanical properties. Therefore metals of high tensile, hardness, and ductility were numerously proposed as a ballistic protection plate [1-5]. Based on mechanics of projectile impact, the penetration of bullets depends on many factors that occur over three phases namely the initial impact phase, stress propagation phase, and fracture initiation phase [6]. During initial impact phase, the projectile kinetic energy is converted in impact energy on the surface or steel plate [7]. The massive force that acts on the plate can be reduced by increasing the hardness of the plate [8]. Once the hardness of the plate is higher than projectile tips, the projectile will shatter and kinetic energy of bullet would be reduced proportionally to its mass [6]. Development of hard protection plate goes back in the 1980s prior to its contribution to penetration resistance. However, hardness increment is only effective up to critical limit because it promotes brittleness in plate that leads to shattering effect [9]. If a protection plate is not hard enough, a projectile tip made from high hardness material with sufficient kinetic energy can penetrate the plate. During impact, balance kinetic energy from projectile exerts large deformation and stress wave on plate over a short period of time. The ability of the plate material to resist bullet perforation depends on the tensile strength [10] where good energy absorption capacity is needed in order to deform the projectiles tips [11]. Moreover, stress wave continues to propagate until the rear side and reflects the waves upon the backplate causing fragmentation of brittle metal (spalling effect). Therefore it is essential for protection plate to have sufficient ductility. This allows plate to bend so it can absorb the stress of impact at high velocity without shattering [12, 13].

Current light vehicle armour used by Malaysia Armed Forces, SIBMAS is utilising monolithic rolled homogenous armour (RHA) as its protection panel as shown in Figure 1. However, the thick monolithic panel is heavy and causes limitations on vehicle mobility. Therefore weight reduction approach has been implied towards protection panel design. One of the most common methods for weight reduction while maintaining its strength is to embrace composite protection panel. The design of laminate must retain the original strength, while reducing the weight of panel [14-16]. As studied, the front material of protection panel must consist of high hardness, whilst the back plate has high ductility. Die to this reason, it is essential to identify the alternative front metal panel to replace the RHA. The protective panel of light armour vehicle will experience mainly ballistic and bending load. Therefore the alternative replacement must be evaluated as per actual condition. But the preliminary study must be limited on basic mechanical properties, such as tensile and hardness of the metal. The tensile strength and hardness of metal relies on several factors but primarily the microstructure. The final microstructure of material is a result of series of heat treatment. Heat treatment can be categorized by austenizing, quenching and tempering.

Tempered martensitic matrix contributes higher hardness as the decreasing of grain size by carbon precipitation [17]. The effectiveness of tempering is further supported by [18] in his study which reveals that high hardness is obtained when tempering of amour material was done at 200 °C due to the stress relief annealing effect. Grain boundary effect has been studied by [19] where smaller grain size increases tensile strength. Other than that, tempered bainite steel was reported to exhibit superior hardness and toughness when contacting armour piercing 7.62 mm caliber projectile [20]. Also, the percentages of alloying elements are very important for precipitating carbide particles. With proper heat treatment process, the precipitation of carbide particles can contribute to high strength in the steel structure [21]. It is also noticed that boron, carbon, manganese, and nickel elements play a main role to improve ballistic properties of armour material [22]. In this study, mechanical properties of three different steels i.e. AISI4340, RHA, and AR500 are compared by tensile and hardness test. The result obtained will be analysed based on its microstructural and composition properties. The purpose of the present work is to preliminarily evaluate the tensile strength, ductility, and hardness of the high strength low alloy steel as alternative front panels to replace the existing RHA. The findings for this paper will benefit as base study for metal selection in future test which includes bending and ballistic testing.

METHODS AND MATERIALS

Material Selection

The materials used in this study were three types of high strength low alloy steel suitable for ballistic application namely rolled homogenous armour (RHA) steel, ABREX abrasion-resistant steel (AR500), and AISI 4340 steel plate [23-25]. RHA is most commonly utilised on high strength steel in armoured vehicles due to its high tensile strength and toughness. The RHA steel used in this study was taken from the door of a 6x6 infantry fighting vehicle of the Malaysian Armed Forces, SIBMAS AFSV-90 armoured vehicle as shown in Figure 1. Besides RHA, AR500 and AISI 4340 are gaining popularity due to their lightweight properties. AR500 is specifically known for its abrasion resistant properties and AISI 4340 has a well balance tensile, toughness, and wear resistance according to local manufacturers.

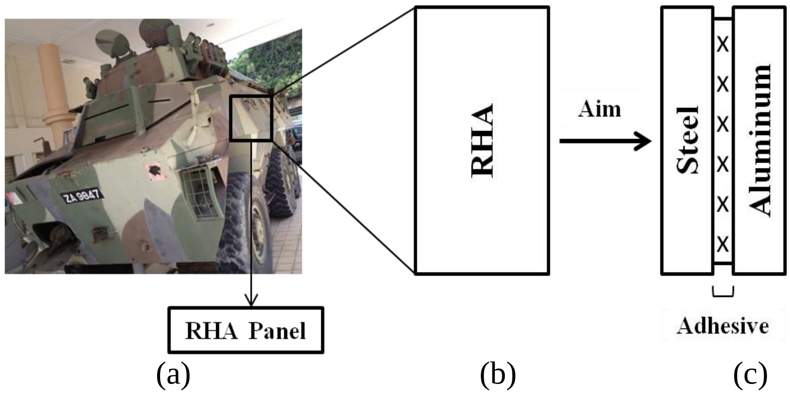


Figure 1. High strength low alloy steel for ballistic application (a) SIBMAS (b) monolithic panel utilised currently (c) proposed laminated panel.

Experimental Procedure

Specimens for microstructure, spectrometer elemental analysis, hardness, and tensile tests were cut using Fanuc C400iA EDM wire cut so that the analysed cross section surfaces were in perpendicular direction to the rolling direction of the rolled plate as shown in Figure 2. The dimension of spectrometer analysis and microstructure specimen was 10 mm × 10 mm × 10 mm. METEX spectrometer was used to identify the percentage of alloying elements in all steels with three times repetition in order to obtain accurate data. Then, for microstructure specimen were grinded from 240, 400, 800, and 1200 grit of SiC sand papers before being polished using 3- and 6-micron diamond suspensions to get a mirror-like surface. Nital (3% HNO_3) was used for etching to reveal the microstructure. The specimens are pictured with magnification ×50 using optical microscope for metallographic examinations.

Figure 3(a) shows the size and dimension of tensile test specimen. Specimen was prepared based on the ASTM E8. The cross section and the length of the gauge area were 6×6 mm^2 and 25 mm, respectively. Tensile test was performed on a Zwick Roell Z100 universal testing machine of 100kN capacity as shown in Figure 3(b). Sample was strained at a cross head speed of 1.5 mm/min to obtain the stress-strain curve for mechanical properties analysis. In measuring the hardness of the tested materials, Rockwell hardness tester of Shimadzu was used for C scale hardness measurement as shown in Figure 4. Indentations were performed on three points to get an average hardness value.

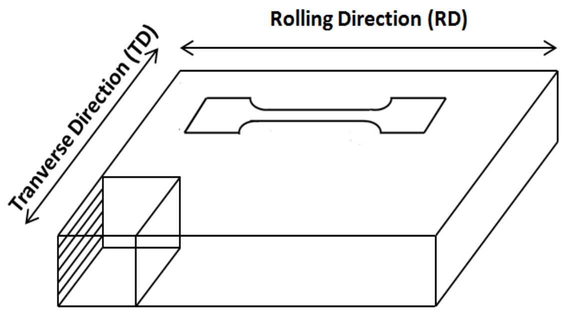


Figure 2. Specimen cutting from rolled plate.

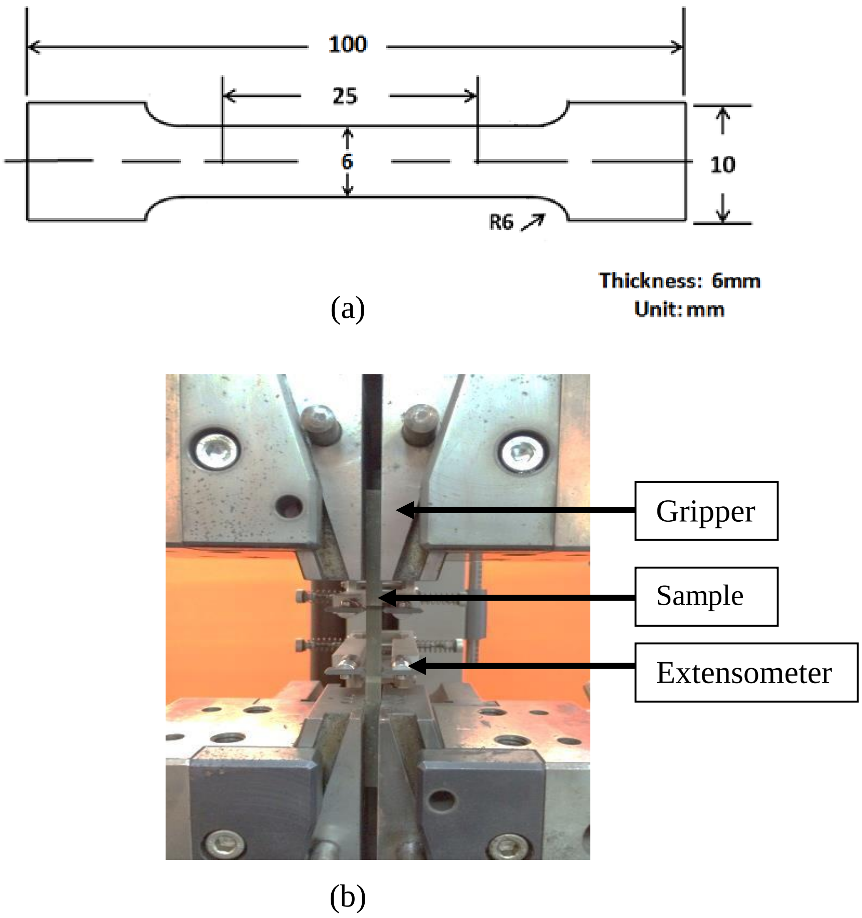


Figure 3. (a) Tensile test sample size and dimension, and (b) tensile testing configuration.

Figure 4. Hardness test using Shimadzu.

RESULTS AND DISCUSSION

Alloying Elements

Table 1 shows the chemical composition of RHA, AISI 4340, and AR500. Composition comparison was highlighted between RHA and AR500 since both steels were heat treated to martensitic phase prior to ballistic requirement. Carbon content in AR500 was found higher than that in RHA. Apart from carbon, AR500 also exceed in manganese and boron compared to other steels, whilst RHA has higher content of nickel compared to AR500. On the other hand, AISI 4340 has exceptionally high content of Nickel compared to in RHA and AR500.

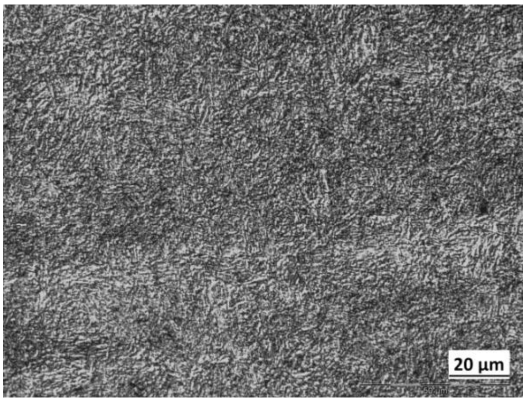
Table 1. Chemical composition of AISI 4340, RHA and AR500 using spectrometer (wt-%).

Materials	Elements									
	C	Mn	P	S	Si	Ni	Al	Cr	Mo	Ti	Fe
RHA	0.20	0.57	0.007	0.009	0.35	0.24	0.02	1.08	0.26	0.06	Bal.
AISI 4340	0.46	1.39	0.013	0.009	0.32	0.89	0.02	1.48	0.20	<0.01	Bal.
AR500	0.40	0.87	0.008	0.011	0.63	0.02	0.07	0.53	<0.01	0.02	Bal.

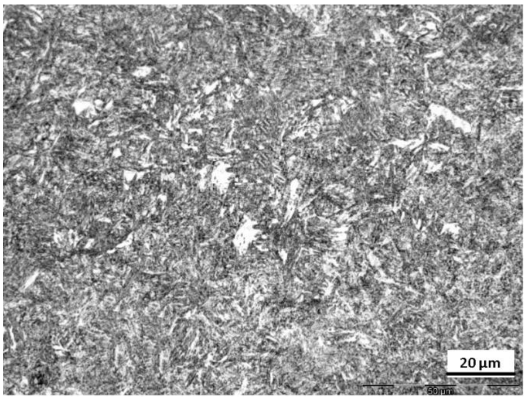
Microstructures

The ballistic performance of armour steel depends on the matrix having tempered martensitic or bainitic structure [22]. This is achieved after application of austenisation, quenching, and tempering on low alloyed steel of AISI 4340, RHA, and AR500 [24-26]. After the process of austenisation and quenching, crystal structure of steel is changed from austenite Face Centered Cubic structure (FCC) into carbon supersaturated Body Centered Tetragonal structure (BCT) to form martensitic or bainitic structure [27]. Then heat treatment of tempering will develop the strength and toughness of the matrix consisting of tempered bainite or martensite [28]. Microstructures of all the low alloy steel plates are given in Figure 5. AISI 4340 steel exhibits coarser grains in bainite phase.

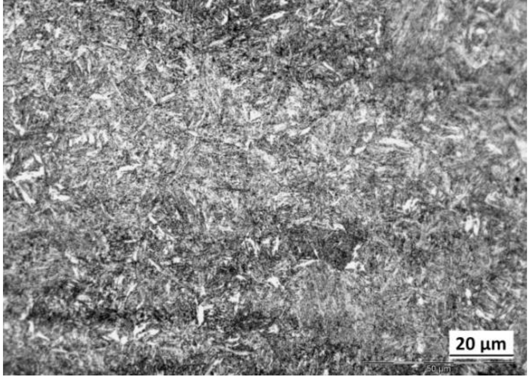
Bainite consists of lath type ferrite and precipitates within ferrite phase and at the boundaries of the laths [29]. Apart from that AISI, 4340 also has increments in retaining austenite as shown in Figure 5(a). Existence of retained austenite is caused by the imperfection during heat treatment process. The retained austenite presence is believed due to the non-uniformity of temperature and cooling rate, where the transformation of austenite phase to bainite phase was not complete uniformly [30]. In addition, retained austenite is a softer phase compared to the martensite, hence the hardness of the material will be reduced [2]. This retained austenite can decrease the strength to defend against the bullet. As shown in Figure 5(b), RHA steel revealed a tempered martensitic phase. Carbide precipitates were observed disperse in the matrix as well. Similar to RHA, AR500 exhibits fine structure and in tempered martensitic phase in Figure 5(c). Tempered martensite consists of recovery and recrystallisation in the matrix to relieve the stress generated during the quenching process [31]. Matrix phase is changed because the carbon atoms move out from the matrix in order to form carbide precipitates [32]. Other than that, banding effect appeared in white shade was captured in the present study. This banding effect is formed due to rolling process. The process of rolling involves cast steel billets of appropriate size and then rolling them into plates of required thickness [33]. Hot rolling changes the coarse grain into the finer grain sizes and increases the mechanical properties [34].



(a) RHA



(b) AISI 4340



(c) AR500

Figure 5. Optical microscopy observation of microstructures in (a) RHA (b) AISI 4340, and (c) AR500.

Tensile Test Analysis

The tensile test results are shown in Figure 6 and summarised in Table 2. Figure 7 shows the bar chart that indicates the error and uncertainty for tensile test value measurement, based on standard deviation and average repetition during experiment. According to the stress-strain curves shown in Figure 6, RHA exhibits the highest tensile strength of 1750 MPa, closely followed by AR500 at 1740 MPa. AISI 4340 recorded lowest tensile at 1020 MPa. This value is 41% lower compared to RHA. The phases in the high strength low alloy steels are believed the main contributing factors for determining the tensile strength of the materials. As seen in Figure 5(b) and 5(c), both RHA and AR500 consist of tempered martensitic phase, reflecting to similar tensile strength values of RHA and AR500.

Nickel is believed to be the main alloying element responsible to increase the strength of steel besides carbon that still maintains its role as a strengthening mechanism [18]. Comparing the chemical compositions, RHA has higher content of nickel compared to AR500. [21] reported that during the tempering process, steel solution rejects carbon in the form of finely divided carbide phases, the high supersaturated solid solution of carbon in iron forming a martensitic microstructure. The final result from the tempering process is a fine dispersion of carbides in an α-iron matrix. Precipitates of carbide particles are present in high strength steel [21], having the black particles as iron carbide. During the tempering process, martensite is decomposed to form carbide particles [35]. This is due to the carbon atoms travelling out of the spaces between the iron atoms [36]. The strain in the martensite is relieved as the carbon atoms leave the matrix. This behaviour contributes to higher strength and hardness [37]. Therefore, it is observable in RHA microstructure tempered martensite with very small iron carbide islands which results in high tensile strength. This is similar to observation made by [38].

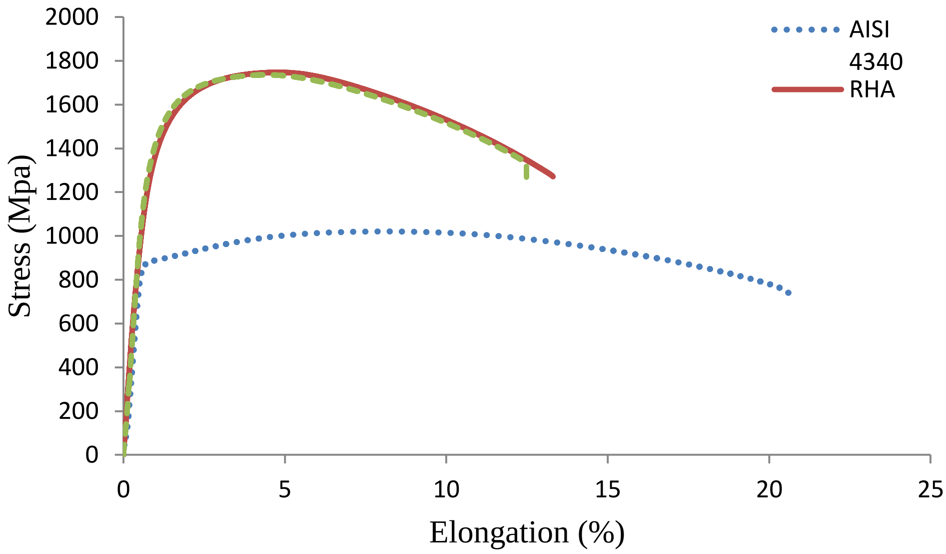


Figure 6. Stress-strain curves for RHA, AISI 4340 and AR500 steels.

The tensile strength of both RHA and AR500 can be further increased by hot rolling process. Hot rolling was performed to homogenise the grain structure of the steel, removing imperfections which would reduce the strength of the steel. Rolling also elongates the grain structure in the steel to form long lines, which enables the stress under which the steel is placed when loaded to flow throughout the metal, and not be concentrated into one area. This can be seen by white banding effect in Figure 5(b-c).

Consequently, both alloys resist stress higher than ordinary steel. Strength increment can finally be increased by resisting dislocations at grain boundaries. Therefore higher amount of grain boundaries in an area resulted in higher strength since it acted as pinning points [39]. This is reflected by RHA fine microstructure, similar to AR500. Based on the study on the impact on steel made by [40], they indicated the potential of RHA and AR500 used as single impact steels with tensile strength, yield strength, and strain falls in the range of 1650-2050 MPa, 1200-1370 MPa and 12-24% respectively.

Meanwhile, RHA and AR500 tops of the tensile strengths AISI 4340 steel exhibit highest elongation at 20.6%, compared to RHA and AR500 at 13.3% and 12.5%, respectively. Based on the microstructure shown at Figure 5(a), AISI 4340 has a bainitic phase with retain austenite appears as white block. Austenite is softer than bainite and martensite. Therefore as reported by [30], the increment of retained austenite reduces hardness and increase ductility of AISI 4340. Apart from that, although a majority element increases strength, nickel was among the few elements that balance the ductility and toughness of the metal. Consequently, the amount of nickel is highest in AISI 4340 as highlighted in Table 1.

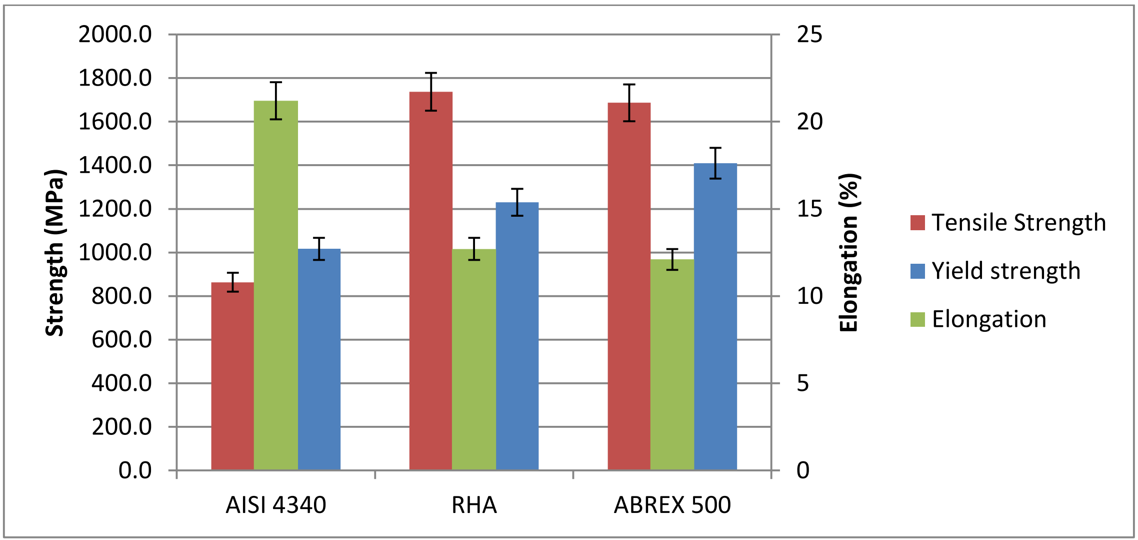


Figure 7. Error bar chart for AISI 4340, RHA and AR500 steels.

Hardness Test Result

The values of hardness are compiled and shown in Table 2. Referring to the hardness properties, AR500 recorded the highest hardness at 47.3 HRC compared to RHA at 43 HRC and AISI 4340 at 34 HRC. There are several factors that contribute to hardness increment primarily its microstructure phase. Hardenability was adequate to achieve by high percentage of martensite [24]. As seen in Figure 5(b) and 5(c), RHA and AR 500 consist of fully martensitic phase. According to the study by [22, 41, 42], martensitic transformation process for RHA and AR500 was enhanced by manganese due to decrement of critical quench speed. Manganese was found to be highest in AR500. Apart from manganese, boron also controls martensitic transformation by preventing bainite and pearlite transformation evidently the amount of boron in AR500 is higher than RHA. Since RHA steel microstructure is also in martensite phase, further hardness of martensite is solely dependent on carbon content.

Table 2. Mechanical properties of RHA, AISI 4340 and AR500 steels.

Material	Young's modulus (GPa)	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Hardness (HRC)
RHA	218	1320	1750	13.3	43
AISI 4340	220	847	1020	20.6	34
AR500	220	1370	1740	12.5	47

Carbon is a very small interstitial atom that tends to fit into clusters of iron atoms. It strengthens steel and gives it the ability to harden by heat treatment particularly if it exceeds 0.25%. Carbon forms compounds with other elements called carbides, such as cementite, exist as precipitate and increase hardness which is mentioned in finding by [43] and [44]. Similar to spectrometer result, carbon content in AR500 was higher than RHA. Consequently, higher hardness could be achieved, as reported by [24]. Besides interstitial carbon that resists slippage, grain boundary also acts as a pinning point to resist dislocations. Fine microstructure as shown in Figure 5(b) and 5(c) consisting of high number of grain boundary in constant area increases resistance to slippage, which improves both tensile strength and hardness. AR500 and RHA represent a tiny of grain boundary that appears invisible. This is also reported by [10] where transformed band produces fine structure increases hardness.

CONCLUSIONS

In this study, the mechanical properties and microstructures of three high strength low alloy steels were investigated. Tensile properties of RHA were found similar to AR500 steel but different from AISI 4340. Tensile strength of RHA, AR500, and AISI 4340 were 1750, 1740 MPa, and 1020 MPa, respectively. Comparing all alloys, AISI 4340 steel showed the highest elongation at 20.6% followed by RHA and AR500 at 13.3 and 12.5%, respectively. RHA and AR500 showed tempered martensitic matrices that contribute to higher hardness due to higher amount of carbon content in martensitic structure. Retained austenite and coarse microstructure of AISI 4340 steel contributed to higher ductility compared to AR500 and RHA. RHA and AR500 exhibited similar tensile properties with higher tensile strength and yield strength compared to AISI 4340. Finer microstructure and full martensite phase in RHA and AR500 contributed to higher hardness and strength. Coarse grain and retain austenite reduced hardness of AISI 4340. The compositional and microstructural effects on mechanical response provide insights in steel armour metal processing. It is concluded that AR500 has a potential to be used to replace RHA as an impact front panel steel for ballistic application.

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