Influence of Heat Input on the Ballistic Performance of Armor Steel Weldments

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INFLUENCE OF HEAT INPUT ON THE BALLISTIC PERFORMANCE OF ARMOR STEEL WELDMENTS

Abstract: *The purpose of this study is to examine the projectile penetration resistance of the base metal and heat-affected zones of armor steel weldments. To ensure the proper quality of armor steel welded joints and associated ballistic protection, it is important to find the optimum heat input for armor steel welding. A total of two armor steel weldments made at heat inputs of 1.29 kJ/mm and 1.55 kJ/mm were tested for ballistic protection performance. The GMAW welding carried out employing a robot controlled process. Owing to a higher ballistic limit, the heat affected zone (HAZ) of the 1.29 kJ/mm weldment was found to be more resistant to projectile penetration than that of the 1.55 kJ/mm weldment. The result showed that the ballistic resistance of heat affected zone exist as the heat input was decreased on 1.29 kJ/mm. It was found that 1.55 kJ/mm does not have ballistic resistance.*

Key words: *armor steel; weldment; projectile penetration; hardness level.*

1. INTRODUCTION

Armor grade steels possessing high strength and hardness are widely used in the production of military armored vehicles such as Lazar III [1]. High hardness armor steel requires carefully controlled welding procedures to avoid hardness losses in heat affected zones [2]. Heat input is the crucial factor associated with the toughness of fusion zones in shielded metal arc-welding weldments [3]. The hardness of armor steel is greatly dependent on the welding temperature history.

HAZ softening occurring during welding of HHA steel and the degree of softening in the HAZ is a function of the weld thermal cycle, which depends on the welding process [4]. GMAW process has a higher deposition rate, compared to the Shield metal arc welding [5]. In application of the GMAW process, the consumable is continuously added and frequent stops are not happening. As a result, the GMAW process has superior productivity compared to SMAW [6]. The pulsed GMAW process can be used in welding armor steel [7] and yields higher productivity than the conventional GMAW process.

Previous studies have shown that a heat input of 1.2 kJ/mm is safe for the ballistic protection of military armored vehicles, whereas a heat input of 1.9 kJ/mm has been found ballistically unsafe for the armor protection of military vehicles. However, a heat input of 1.2 kJ/mm was found herein to be insufficient to ensure the proper quality of armor steel welded joints, so it was of paramount importance to find the optimum heat input for obtaining the best ballistic protection of the welded joints. Appropriate welding parameters are essential for the ballistic resistance of weld joints [8] in military vehicles, as well as their toughness when the vehicles are moving over uneven terrains.

This paper presents a comparison of the ballistic performance of quenchable armor steel weldments made at heat inputs of 1.29 kJ/mm and 1.55 kJ/mm, which form a 100% martensitic structure at a cooling rate of 7 °C/s.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

2.1 Base and Filler Material

Armor steels are well established as projectile-resistant materials. The commercially available Protac 500 armor steel was used in this study for its high strength (σy = 1206 MPa and UTS = 1536 MPa) [9].

The chemical composition (wt. %) of the base metal, armor steel, was 0.27 C, 1.07 Si, 0.706 Mn. 0.637 Cr, 1.09 Ni, 0.3 Mo, 0.039 V, 0.01 S, and 0.02 P. The chemical composition (wt. %) of the filler material, Mn type stainless steel, was 17.76 Cr, 8.24 Ni, 6.29 Mn, 0.89 Si, and 0.08 C. The chemical composition of the welded joint after the welding process was obtained by an ARL 2460 spectrometer

2.2. Welding Process

Gas metal arc welding (GMAW) was performed at heat inputs of 1.29 kJ/mm and 1.55 kJ/mm, using the same welding configuration Fig. 1). A 55 degree single V groove edge with a 4 mm root face gap was employed before welding. Each weld was produced by four pass welding with preheating. The plate dimensions were 500 mm × 250 mm × 11 mm. A water jet cutter was employed for plate cutting and edge preparing.

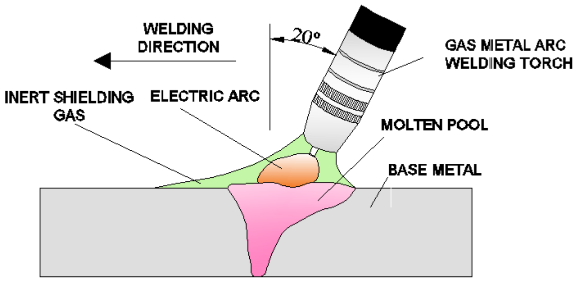


Fig. 1. Schematic drawing of welding process.

The Protac 500 welding parameters are shown in Tab. 1. Welding heat input calculated in accordance with EN 1011-1, using equitation 1. Where heat transfer efficiency was 0.8 for GMAW.

$$Heat\ inp. = \frac{arc\ volt.*\ arc\ cur.*\ heat\ tran.ef.}{travel\ speed} \quad 1$$

The automated welding for both heat inputs considered was performed using the Kuka robot, Augsburg, Germany and the Citronix 400A GMAW welding machine.

Heat Input	Preheat Temp.	Current	Voltage	Welding Speed	Shielding Gas
	[°C]	[A]	[V]	[m/min]	Ar. + 2.5% CO_2
1.29	160	193	25	0.18	
1.55	160	215	25.5	0.17	

Table 1. Welding parameters of the Protac 500 armor steel welding.

2.3 Hardness Measuring

According to the EN ISO 9015-1 standard [10], the hardness of welded joints is measured for their complete characterization. The hardness of the Protac 500 welded joints was herein tested 2 mm under the upper welding surface at heat inputs of 1.29 kJ/mm and 1.55 kJ/mm. The hardness of both heat input samples considered was measured along the fusion line for achieving optimum hardness in this critical zone and along the edge of the weld metal. The Digital Micro Vickers Hardness Tester HVS1000 (Laiznou Huayin Testing Instrument Co., Laizhou City, China) was used for microhardness testing, applying a load of 500 g. Each microhardness value represents the mean value of three measurements performed.

2.4 Ballistic Testing

The ballistic resistance testing in this study was accomplished in accordance with the VPAM APR 2007 standard [11], which stipulates placing the ballistic pipe at a distance of 10 m from the target [12]. The ballistic test scheme and the 7.62 × 51 mm projectile used are shown in Fig. 2 a, b). The projectile speed was measured prior to the experiment at a distance of 7 m from the position of the ballistic pipe mouth. The projectile speed measurements were performed on three projectiles to obtain a representative mean value of the projectile speed.

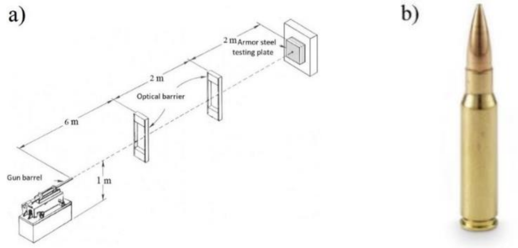
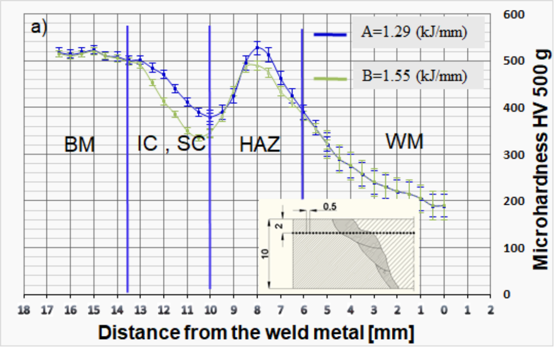


Fig. 2. (a) Ballistic testing scheme; (b) the 7.62 × 51 mm projectile.

3. RESULTS

3.1 Hardness

Hardness is one of the most important aspects of armored vehicle crew protection and the quality of welded joints. The hardness profiles obtained for heat inputs of 1.29 kJ/mm and 1.55 kJ/mm are shown in Fig. 3.



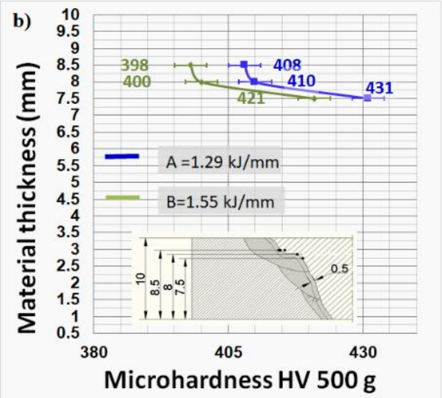


Fig. 3. (a) Hardness distribution of the automated welding at heat inputs of 1.29 kJ/mm (A) and 1.55 kJ/mm (B). (b) Hardness distribution along the fusion line of the automated welding at heat inputs of 1.29 kJ/mm (A) and 1.55 kJ/mm (B). Each hardness value represents the mean value of three measurements performed.

Fig. 3 a) shows the hardness of the welded joints preheated at 150 °C, using an inter-pass temperature of 160 °C. The welded joint zones were marked accordingly with the following abbreviations: WM (weld metal), FL (fusion line), HAZ (heat affected zone), IZ (inter critical zone), SZ (sub critical zone) and BM (base metal).

The hardness profile obtained for a heat input of 1.29 kJ/mm Fig. 3 a) indicates hardness variations in the WM, FL, HAZ and BM zones. The hardness values increased from the middle of the WM zone (190 HV) towards the fusion line, along which a value of 339 HV was recorded on the WM side. The FL hardness value was 410 HV. The hardness values increased in the HAZ zone and reached a maximum value of 521 HV at a distance of 8 mm from the weld axis. The values decreased thereafter and a minimum hardness of 378 HV was recorded at a distance of 10 mm from the weld axis.

Upon another subsequent increase, the hardness values eventually leveled off at 509 HV recorded at a distance of 14 mm from the weld axis, which also marked the limit of the HAZ and OM zones. The average BM hardness value was 509 HV.

The hardness profile obtained for a heat input of 1.55 kJ/mm Fig. 3 b) also suggests hardness variations in the WM, FL, HAZ and BM zones. The hardness values increased from the middle of the WM (192 HV) towards the fusion line, along which a value of 350 HV was recorded on the WM side. The FL hardness was 400 HV.

The hardness values decreased in the HAZ zone and reached a minimum value of 325 HV at a distance of 10.5 mm from the seam axis. Upon another subsequent increase, the hardness values eventually leveled off at 509 HV recorded at a distance of 14 mm from the seam axis, which also marked the limit of the HAZ and OM zones. The average BM hardness value was 509 HV.

The hardness of the 1.29 kJ/mm and 1.55 kJ/mm weldments was measured along the fusion line Fig. 3 b). The results obtained show that the fusion line hardness of the 1.29 kJ/mm weldment ranged between 408 HV and 431 HV, whereas the fusion line hardness of the 1.55 kJ/mm weldment ranged between 398 HV and 421 HV. The hardness values were found to be associated with heat effects: the heat effect was more significant in the zones closer to the cover pass, whereas the already cooled additional and base material reduced the heat effect in the more remote zones.

3.2 Microstructure

The microstructure of the coarse-grained HAZ region of the 1.29 kJ/mm weldment Fig. 4 a) indicates the formation of smaller volume fractions of softer constituents, i.e., lower and upper bainite. The 1.55 kJ/mm weldment Fig. 4 b) consisted of a mixture of lath martensite and upper and lower bainite. The martensite to bainite (upper + lower) ratio determined was approximately 40:60. With an increase in heat input to 1.55 kJ/mm, an increasing amount of bainite was observed. However, the martensite content diminished in the microstructure of the coarse-grained region near to the fusion line. Such conditions favored the formation of bainite with a predominant amount of upper bainite in the microstructure of the 1.55 kJ/mm welded joints.

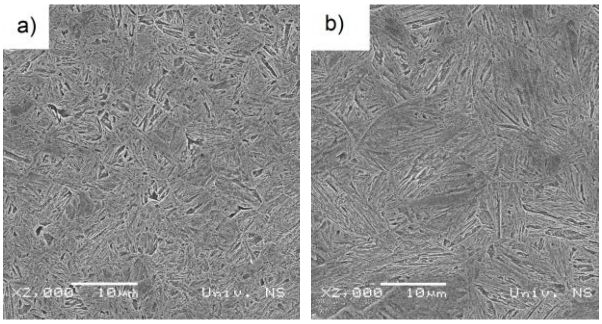


Fig. 4. SEM microstructures of the coarse-grained HAZ (a) of the 1.29 kJ/mm weldment. SEM microstructure of the coarse-grained HAZ (b) of the 1.55 kJ/mm weldment.

3.3 Ballistic Test Results

The results of ballistic resistance testing of the welded Protac 500 joints made at a heat input of 1.55 kJ/mm are given in Tab. 2). The results obtained show that the initial velocities of the 7.62 × 51 mm projectile ranged from 854.896 m/s to 848.881 m/s. The equivalent shooting distance was 10 m. Two punch holes were made in this zone in the first two shootings, whereas a bulge with a protrusion was made in the third shooting.

The damaged HAZ area was in the range of 70.24–90.6 mm^2. The damage on the inside of the heat-affected zone indicates intense plastic deformation in the direction of the projectile's passage.

The initial projectile velocities recorded in the HAZ area of the 1.29 kJ/mm weldment ranged from 850.231 m/s to 852.142 m/s Tab. 2). The equivalent shooting distance was 10 m. Two plastic flows were made in this zone in the first two shootings, whereas a protruding bulge was made in the third shooting. The damaged HAZ area was in the range of 60.9–80.6 mm^2 The hardness of the HAZ zone ranged from 358 HV to 521 HV.

The initial projectile velocities recorded in base metal of the 1.29 kJ/mm weldment ranged from 849.116 m/s to 852.213 m/s. The equivalent shooting distance was 10 m. Three bulges were made in this zone in three shootings. The damaged base metal area was in the range of 30.9–40.6 mm^2.

Serial Number	**Heat Input**	**Position**	**Initial Speed V10**	**Equivalent Shooting Distance**	**Angle of Impact Relative to the Projectile Trajectory**	**Type of Damage**
	[kJ/mm]		**[m/s]**	**[m]**	**[°]**	
4	1.55	HAZ	852.142	10	90	punch hole
5	1.55	HAZ	851.321	10	90	punch hole
6	1.55	HAZ	850.231	10	90	bulge
7	1.55	Base metal	849.116	10	90	plastic flow
8	1.55	Base metal	850.212	10	90	plastic flow
9	1.55	Base metal	852.313	10	90	plastic flow
10	1.29	HAZ	852.048	10	90	bulge
11	1.29	HAZ	851.254	10	90	bulge
12	1.29	HAZ	850.358	10	90	bulge
13	1.29	Base metal	849.742	10	90	plastic flow
14	1.29	Base metal	850.343	10	90	plastic flow
15	1.29	Base metal	852.259	10	90	plastic flow

Table 2. Results of ballistic resistance testing of the welded Protac 500 joints made at a heat inputs of 1.29 and 1.55 kJ/mm.

4. DISCUSSION

The microstructure formed in the HAZ is a function of the chemical composition of the steel considered and the weld thermal cycle. The main concern when employing higher heat inputs in the HHA steel welding (namely a heat input of 1.55 kJ/mm) is the formation of wide extensively softened areas in the over-tempered region that could compromise the ballistic performance of the welded structure. Conversely, the resulting prolonged cooling times temper its rehardened HAZ areas, thus reducing the risk of HACC. These effects could compensate for employing the proposed low level preheating in multi-pass joint welding.

The microhardness HAZ values of the 1.29 kJ/mm weldment ranged from 390 HV to 523 HV, whereas the microhardness HAZ values of the 1.55 kJ/mm weldment ranged from 325 to 490 HV. It is concluded that as heat input decreases, the hardness of the weld metal increases, which leads to ballistic protection.

Changes in the base material hardness of the 1.29 kJ/mm and 1.55 kJ/mm weldments occurred at distances of 13.5 mm and 14.2 mm from the weld axis, respectively. From a perspective of armor protection and ballistic resistance to small arms projectiles, the selection of a heat input is important because it greatly affect the hardness of the HAZ coarse-grained area. A previous study reported that coarse-grained zone hardness values of 541 HV and 502 HV were recorded in the 0.8 kJ/mm and 1.6 kJ/mm weldments [13]. These results are similar to the results obtained in the present study. A hardness value of 523 HV was recorded in the 1.29 kJ/mm weldment. This slightly higher hardness was achieved due to the increased hardenability of Protac 500. With a heat input of 2.37–1.33 kJ/mm, the AISI 4340 armor steel was found to have a coarse-grained zone hardness of 403–430 HV [14]. The maximum coarse-grained hardness of 443 HV was achieved with a heat input of 2.37 kJ/mm [15].

The hardness results obtained show that lower heat inputs practically improve the hardness in the coarse-grained HAZ subzone. Moreover, little to no softening was observed in the over-tempered area of the optimized welds, with the hardness values exceeding the lowest hardness value of 509 HV permitted by MIL-STAN-1185 at a distance of 15.9 mm from the weld.

The results of the HAZ ballistic resistance testing for the 1.29 kJ/mm and 1.55 kJ/mm weldments, using 10 mm metal sheets, are given in Tab. 2. None of the three 7.62 × 51 mm projectiles fired made a punch hole in the 1.29 kJ/mm weldment. However, one of the projectiles punched through the HAZ zone of the 1.55 kJ/mm weldment. This can be explained by the diminished hardness of this zone compared to that of the 1.29 kJ/mm weldment.

The results of ballistic resistance testing in the base material zone of the 10 mm thick Protac 500 plates considered are presented in Tab. 3. None of the three 7.62 × 51 mm projectiles fired made a punch hole in this zone, which can be accounted for by the optimal ductility of the zone (reflected also in the low plastic deformation sustained). Therefore, the 10 mm thick Protac 500 plate was found to provide the required degree of the base material ballistic protection. The results of ballistic resistance testing in the base material zone show unequivocally that hardness is the predominant mechanical property of high and ultra high strength materials compared to tensile strength, yield stress and impact energy. Slight grain penetration was observed in the 1.29 kJ/mm weldment HAZ whereas no grain penetration was recorded in the 1.55 kJ/mm weldment HAZ.

The ballistic results obtained indicate that a heat input of 1.29 kJ/mm was found to be the limit for achieving the desirable armor protection and HAZ ballistic resistance of armor steels forming a 100% martensitic structure at a cooling rate of 25 °C/s. A higher heat input would impair the HAZ ballistic resistance of such steels. In the case of Protac 500, the limit for preventing grain penetration is a heat input of 1.55 kJ/mm. A heat input greater than 1.55 kJ/mm would impair the ballistic resistance of the Protac 500 HAZ.

5. CONCLUSIONS

Two armor steel GMAW weldments made at heat inputs of 1.29 kJ/mm and 1.55 kJ/mm were tested for ballistic protection performance.

On the basis of the results obtained, the following conclusions can be drawn:

- The hardness of the HAZ fusion zone diminished at a heat input of 1.55 kJ/mm, resulting in the reduced ballistic protection of armored vehicles. Welded metal hardness is increased with the decrease in heat input.
- The microstructure in the CGHAZ changes from lath bainite / martensite to coarse granular bainite with increasing heat input.
- An increase in heat input leads to a ductile domain, thus reducing the ballistic performance of the 1.55 kJ/mm weldment. In the case of the 7.62 mm AP projectile, hardness and strength of the material are important for ballistic performance. There fore, the 1.55 kJ/mm weldment was found not to be resistant to the 7.62 × 51 mm projectile penetration.

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