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Ballistic Behaviour of Austempered Compacted Graphite Iron Perforated Plates

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ABSTRACT

In this study, the performance of austempered compacted graphite iron was evaluated to find its suitability as perforated plates used in add-on armour. Perforated compacted graphite plates were subjected to austenitisation at 900 °C for 2 h followed by austempering at 275 and 400 °C for 1 h. The basic plate was fixed at 400 mm away from the perforated plate and armour and then piercing incendiary projectile was shot from a distance of 100 m. It was observed that both 7 mm and 9 mm perforated plates austempered at lower temperature of 275 °C producing higher hardness and lower ductility were effective in fracturing the penetrating core, thereby significantly decreasing the chances of penetrating the basic plate.

Keywords: Austempered compacted graphite iron; Perforated plates; Ballistic protection

1. INTRODUCTION

Compacted graphite iron (CGI) is a special type of cast iron containing graphite of short lamellar type, behaving in between grey iron with lamellar graphite and ductile iron with spheroidal graphite, but containing lower amount of spheroidisers/nodularisers (cerium and magnesium)[1-4]. To enhance mechanical properties, CGI can be heat treated to obtain austemperted compacted graphite iron (ACGI)[5-7] following transformation of initial ferrite, ferrite-pearlite or pearlite matrix into a unique ausferritic microstructure involving alternate acicular laths of ferrite and carbon stabilised retained austenite[8,9]. In spite of being less ductile, it may be used as perforated plates for applique ballistic protection of military vehicles[10]. Usually, perforated plates are made of various type of heat treated steels[11-13] and ADI materials[14]; however, when combined with armour system together with basic armour plate, they can offer a relatively high mass effectiveness due to the phenomenon of stress induction in the projectile penetrating core. Subsequent appearance of bending stress causes fracture of the hard and brittle penetrating core, thereby lowering the depth of penetration[15,16]. Following such practice, the cracks propagate only to nearest perforation, thus resulting in an increase in resistance of the armour system to crack-driven failure[13,14,17]. Beside this, the amount of critical raw materials initially required during melting is minimal, roughly half to that in ADI (around 0.03 wt. % Mg) as well as in armour steel (up to 2.0 wt. % Cr and 1.0 wt. % Mo) and the ACGI is simpler to produce than ADI[5,18].

In the present work, conventional metallography, direct comparison, and the Rigaku diffractometer technique are used to characterise the microstructural properties of ACGI. In addition, tensile and hardness behaviour are studied and finally the perforated plates of ACGI are ballistically tested as an essential part of armour system together with the basic plate.

2. EXPERIMENTAL

Base CGI was fabricated by magnesium treatment of molten bath (with low sulphur) adding Mg-Fe-Si alloy to obtain castings with compacted graphite bearing 20 per cent nodularity in a metallic matrix containing mainly pearlite. Chemical composition of the base alloy, determined by optical emission spectroscopy shows the following elements in wt. %: C-3.71, Si-2.01, Mn-0.18, Cu-0.018, Cr-0.015, Mg-0.014, P-0.038, S-0.011 and balance Fe. Castings of dimension 210 mm (length) x 130 mm (breadth) and with two different thicknesses of 7 mm and 9 mm were perforated in a Heidenreich and Harbeck FM-38 CNC milling machine to produce mm perforations keeping ligament length between holes as 3.5 mm. Perforated castings or plates were subjected to austempering treatment comprising of austenitisation at 900 °C for two hours followed by isothermal holding at 275 °C and 400 °C in respective salt bath for 1 hour at each temperature to produce ACGI-275 and ACGI-400 materials.

Metallographic samples were prepared by standard practice of cutting, grinding, polishing and etching with 3 per cent (by volume) vital before light microscopic examination. Heat tinting comprising of heating etched ADI samples at 260 °C for 6 h was done to reveal the presence

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of different phases in terms of colour, namely, blue for low carbon reacted metastable austenite, purple to red for high carbon reacted stable austenite, white for carbides, beige for ausferritic ferrite and light grey for martensite with lenticular shape. Vickers micro-hardness was measured on each identified phase using 25 g load in a Wilson Tukon 1102 machine; while macro hardness was measured in a VEB HPO-250 machine under 10 kgf load and taking average of five random measurements. Further, tensile properties were obtained as an average of five repeated tests on each heat treated sample in VEB ZDM 5/91 mechanical testing machine; whereas JWT-450 instrumented impact testing machine was used to determine impact energy of un-notched specimens. Crack initiation and crack propagation energies were obtained from the machine, as energies before and after maximum force was measured, respectively.

Volume fraction of retained austenite in the microstructure of ACGI was measured using an Ultima IV Rigaku diffractometer with Cu kα radiation in a 2θ range of 35 to 90^{o}. The x-ray generator was operated at 40 kV and 40 mA. Each sample was scanned with 5^{o} per min rate three times and direct comparison of diffractograms was used in accordance to Cullity[19].

Ballistic testing was conducted on perforated plates combined with basic 13mm armour plate keeping 400 mm gap in between. The armour test set-up was perpendicular to the projectile trajectory aiming to improve protection from the level of 7.92 x 57 mm armour piercing (AP) to the level of 12.7 x 99 mm armour piercing incendiary (API) shot. These two types of ammunition were chosen as standard in SNO 1645 standard[20]. For each test, five shots were fired from M2 machine gun from a distance of 100 m under surveillance of BS-850 velocity-radar positioned 10 m away and the protection criterion was set at five non-penetrating shots as described in[20]. Following are the basic plate damage description[21] characterising complete penetration through perforated and basic plate as hole normal (HN), a bulge on basic plate back with one crack as crack bulge (CB) and a bulge on basic plate back with no crack as smooth bulge (SB). Since the perforated plate aims at fracturing the penetrating core, number of fragments so produced has been added to the said damage description. Multi-hit resistance is described by the number of interconnected holes following fracture and the area involving the interconnected holes.

Damaged is the area that is fractured off the perforated plate, together with the area or the remaining plate with the distance from the fracture line of *h*, providing that *h/R* ratio is 0.34 (R-core radius). In case of a lower *h/R* ratio, the core fracture may not occur, as recommended by Chochron[15].

3. RESULTS

3.1 Microstructure and Mechanical Properties

Polished CGI surface, as given in Fig. 1(a), reveals warm-like appearance of graphite with rounded edges appearing on un-etched matrix. Whereas, polished and etched surface of ACGI 275 in Fig. 1(b) shows fine and dense acicular ferrite plates separated by relatively thin layer of retained austenite and that of ACGI 400 in Fig. 1(c) shows coarse ferrite and bulk retained austenite sandwiched between ferrite plates. Mechanical properties arising out of tensile, hardness and impact tests are as presented in Table 1 where crack initiation and crack propagation energy values are also reported based on load-displacement chart as given in Fig. 2.

As evident in Table 1, the higher strength (YS and UTS) and hardness along with a corresponding less absorption of impact energy of ACGI 275 material match well with its finer ausferritic microstructure. Whereas, the degraded tensile and hardness behaviour of ACGI 400 material correlates with its matrix bearing coarse ausferrite. Further, the data in Table 1 clearly exhibit a direct correspondence between higher impact energy and higher volume fraction of retained austenite in ACGI 400.

Table 1. Properties of ACGI materials

Material	YS (0.2% offset) [MPa]	UTS [MPa]	Elongation A [%]	Crack initiation energy K0 [J]	Crack propagation energy K0 [J]	Impact energy K0 [J]	HV10	Volume fraction of retained austenite X_γ [%]
ACGI-275	1310	1364	1.3	7	2	9	490	9.5
ACGI-400	668	840	3.1	32	6	38	294	25.2

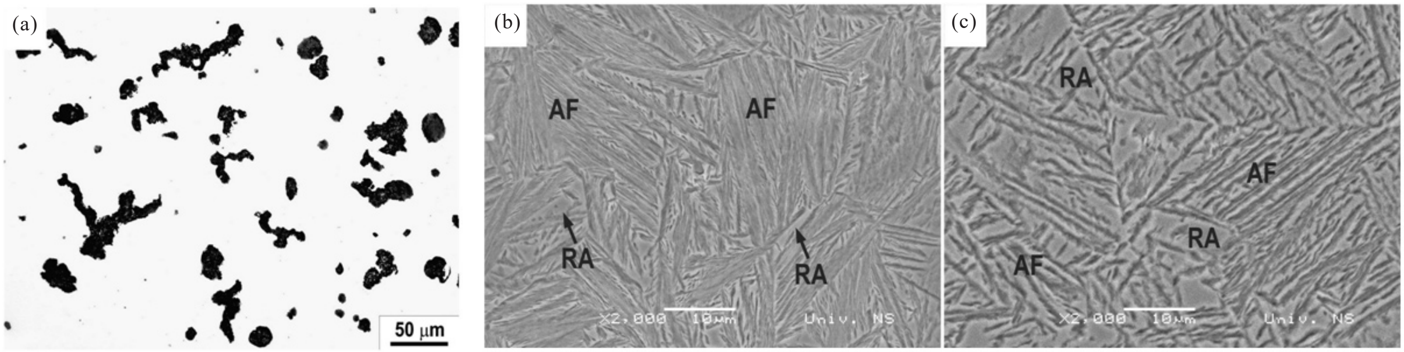

Figure 1. Microstructure of (a) Polished and un-etched CGI, (b) polished and etched ACGI 275, and (c) polished and etched ACGI400.

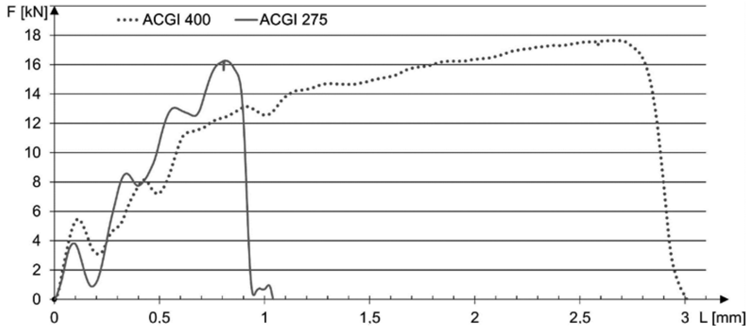

Figure 2. Instrumented charpy pendulum load-displacement chart.

3.2 Ballistic Testing

Results of ballistic tests are given in Table 2. ACGI 275 fully satisfies the set ballistic protection criteria involving large damage area to each plate. ACGI 275 - 7 mm thick plates suffer from three penetrating core fractures out of five shots fired; while the thicker ACGI 275 - 9 mm plates appear to be more efficient showing all penetrating cores fractured. In this context, it important to note that as the number of fragments is higher and the associated damage area is large, the scope of damaging basic plate is reduced a lot. Such a superior behaviour of ACGI 275 - 9 mm plate is due to control damage area involving reasonably good number of interconnected holes. ACGI 400 perforated plates do not satisfy the ballistic criteria due to penetration occurrence. The lower average damage area and number interconnected holes in this material is attributed to its higher ductility and the associated poor strength and bulk hardness.

3.3 Material Behaviour under Gun-shotimpact

Pictorial evidences highlighting the effect of shot number 6 and 17 are as given in Fig. 3 for ACGI 275 - 9 mm perforated - basic plate combine and ACGI 400 - 9 mm perforated - basic plate combine, respectively. ACGI 275 - 9 mm perforated plate suffers from relatively minor damage involving six interconnected holes (Fig. 3(a)). Subsequent effect of fractured core on the corresponding basic plate face is as shown in Fig. 3(b) exhibiting three dents developed by penetrating core fragments. Similarly, ACGI 400 - 9 mm perforated plate suffers from a damaged edge again with six interconnected holes (Fig. 3(c)) and the corresponding basic plate damage is depicted

Table 2. Ballistic testing results

Add-on plate	Shot number	Muzzle velocity v_{10} [m/s]	Number of interconnected holes	Damaged area [mm^2]	Base plate observation
ACGI-275, 7 mm	1	871	6	945	SB (two fragments)
	2	873	7	1330	CB (two cracks)
	3	870	8	1652	SB (three fragments)
	4	876	6	1114	SB (two fragments)
	5	879	12	2214	CB (one crack)
Average		874	7.8	1451	
ACGI-275, 9 mm	6	869	6	822	SB (three fragments, Fig. 3b)
	7	875	6	866	SB (two fragments)
	8	870	5	623	SB (unknown number of fragments)
	9	876	7	1241	SB (unknown number of fragments)
	10	872	5	602	SB (three fragments)
Average		872	5.8	831	
ACGI-400, 7 mm	11	869	6	784	CB (two cracks)
	12	880	5	558	CB (one crack)
	13	877	6	845	HN
	14	871	5	627	HN
	15	875	6	851	HN
Average		874	5.6	733	
ACGI-400, 9 mm	16	875	5	420	SB
	17	872	6	963	HN, Fig. 3(d)
	18	870	5	402	SB (two fragments)
	19	869	6	741	HN
	20	865	4	360	SB (two fragments)
Average		870	5.2	577	

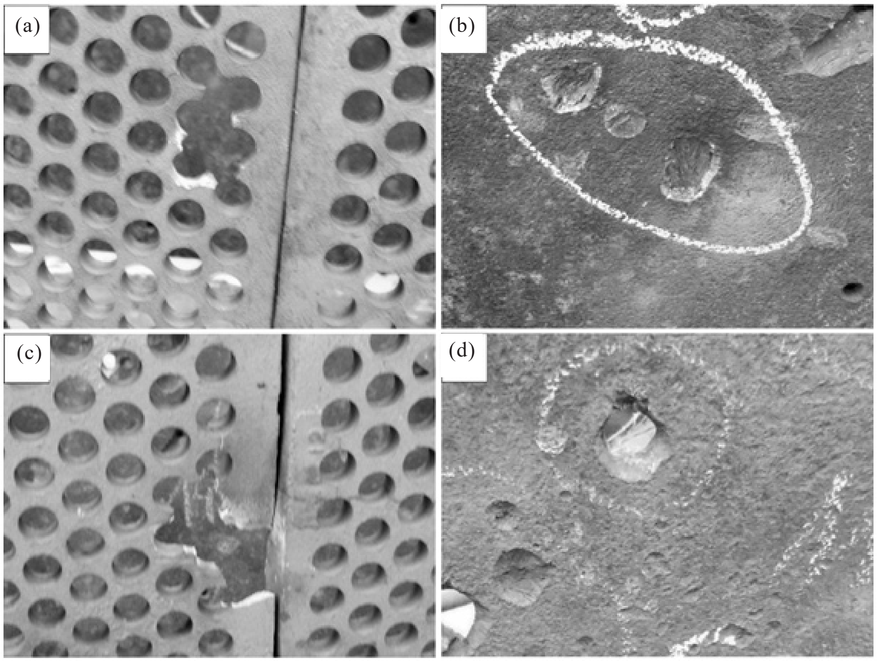

Figure 3. Effect of impact: (a) shot number 6 on ACGI 275 9 mm perforated plate, (b) corresponding basic plate, (c) shot number 17 on ACGI 400 9 mm perforated plate, and (d) corresponding basic plate (d).

in Fig. 3(d) revealing a typical extension of penetrating core even through the basic plate with yawing.

3.4 Microstructure and Microhardness after Gun-Shot Impact

Microstructures of ACGI 275 and ACGI 400 perforated plates following impact by gun-shots are as shown in Fig. 4 in etched and heat tinted condition. Both in Figs. 4(a) and 4(b), the microstructure is ausferrite containing alternate plates of dark/grey ferrite and reddish retained austenite along with low carbon reacted metastable austenite and light grey or off-white martensite islands. Significant amount of martensite appears after impact on ACGI 400 perforated plate.

Microhardness profile of heat tinted microstructure after impact on ACGI 400 perforated plate is as shown in Fig. 4(c). Higher hardness of 762 HV corresponds to off-white martensite area; while relatively lower hardness of 587 HV and 514 HV suggest the presence of retained austenite and martensite in variable proportions at the concerned locations. In comparison to the above, the ausferritic region containing dark ferrite and reddish retained austenite gives rise to minimum hardness of 237 HV.

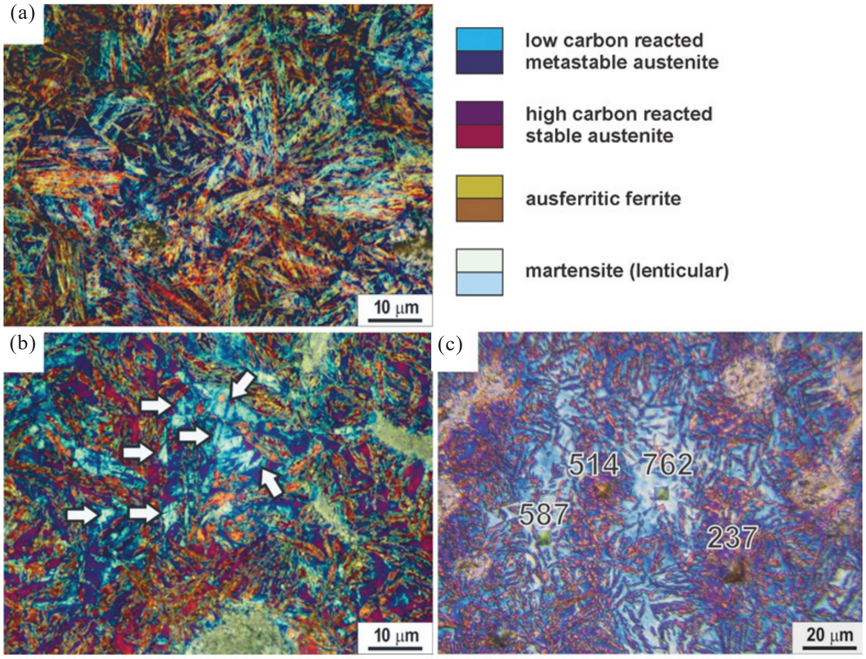

Figure 4. Heat tinted micrographs after gun-shot impact on perforated plates: (a) ACGI 275, (b) ACGI 400, and (c) ACGI 400 with indicated microhardness values.

4. DISCUSSION

Considering the similarity in weight with perforated ADI plates[14] as well as 6 mm steel plates[13] and also analysing the ballistic performances noted in the present study, ACGI 275 7 mm perforated plates happen to be a better choice as add-on armour for military vehicle. However, the lower multi-hit resistance of ACGI 275 involving higher number of interconnected holes and higher damaged area provides no such serious limitation for the purpose. In addition, the upcoming technological level and lower cost of fabrication add an extra flavour to this innovative choice of ACGI 275 with suitable thickness. Although, ACGI 275 9 mm thick offers a higher multi-hit resistance, its greater weight sets a limit when used as add-on armour. As to correlate the ballistic test performance with materials microstructure, finer ausferrite microstructure and the associated stress induced transformation of retained austenite to martenste during gun-shot impact make ACGI 275 perforated plates most suitable fulfilling ballistic protection criteria. In comparison, ACGI 400 perforated plates, although involve post-impact smaller number of interconnected holes and lower damaged area as shown in Table 2, do not provide sufficient fracture potential and therefore do not fulfil the said ballistic protection criteria.

While comparing the mechanical properties of ACGI 275 and ACGI 400 with that of steels used in previous studies[13,14,17], although ACGI 275 displays considerably lower ductility (Table 1), but the comparable hardness values of ACGI 275 and steels (e.g. 490 HV versus 445 BHN in Hardox 450 and 465 BHN in 50CrV4 steel hardened and tempered) become a deciding factor towards evaluating ballistic performances. In another attempt[17], 50CrV4 perforated plate with lower (6 mm) thickness is heat treated to achieve higher hardness of 598BHN, but tested unsuccessful to fulfil ballistic protection criteria. This suggests that hardness is not a proper substitute of thickness in order to improve the ballistic performance.

Microhardness profile in Fig. 4(c) correlates well with the distribution of phases appearing therein. It is likely that following gun-shot impact on a perforated ACGI plate, regions bearing low carbon metastable austenite undergo stress-induced transformation to martensite and such a phenomenon is responsible for localised high microhardness values in Fig 4(c). Although, stress-induced transformation of austenite to martensite has a positive effect on materials performance[23-26] during wear and cavitation; but this is not true in case of perforated ACGI plate when subjected to gun-shot impact, because the localised martenste transformation decreases the multi-hit resistance through initiation and propagation of cracks during impact.

5. CONCLUSIONS

Given the experimental conditions and limitations, and shown results, the following can be stated:

- 7 mm and 9 mm thick CGI perforated plates, austempered at 275 °C and combined with basic armour plate provides full ballistic protection against 12.7 mm x 99 mm API ammunition.
- CGI perforated plates austempered at 400 °C is not suitable for ballistic protection following their poor strength and hardness.
- Selection of ACGI 275 perforated plate as suitable add-on armour is considered unique purely based on its finer ausferritic microstructure.
- Increased localised hardening due to stress-induced transformation of retained austenite to martensite happens to be an additional deciding factor while selecting ACGI add-on armour.
- Large damaged area involving more number of interconnecting holes is likely to provide the ACGI perforated plate poor multi-hit resistance compared to steel perforated plates.

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Contribution in the current study he designed the experiment, damaged area calculation, interpretation of data, wrote the paper.

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Contribution in the current study, he did mechanical property testing, editing the paper.

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Contribution in the current study, she did text editing and corrections.