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Ballistic Efficacy of Carbide Free High Strength Nano-Structured Bainitic Armour Steels

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ABSTRACT

Carbide free nano-structured bainitic steels typically have strength more than 2.0 GPa and impact toughness of 7 J or less. Most of this class of steels have sluggish kinetics and takes 16-72 h for complete bainitic transformation. The present work discusses key perspectives in developing carbide free nano-structured bainitic steel having strength more than 2.0 GPa and toughness more than 15 J. Further, ballistic evaluation of newly developed carbide free nano-structured bainitic steels having strength more than 2.0 GPa and high toughness of 20 J was carried out to understand the adaptability of these steels in combat vehicle applications. A comparison is made between newly developed high strength and tough carbide free nano-structured bainitic steels with typical martensite based ARMOX 500 class of armour steels. The developed nano-structured bainite showed ballistic performance much superior to ARMOX 500 steel. Monolithic plates of bainite provide complete protection against 7.62 AP projectiles at an areal density of 120 kgm-2. The ballistic efficiency of monolithic plates was further enhanced by using perforated geometrical configurations.

Keywords: Ballistic; Nanobainite; Strength; Toughness

1. INTRODUCTION

Armour steels are typically categorized into various classes (up to class 8 as per DEF-AUST-8030, MIL-STD etc.) based on their hardness values and ballistic performance against particular application. Of these, armour steels having hardness up to 530 VHN (class 1-6) are well defined as per MIL-STD-12560 and MIL-STD-46100[1-3]. With increase in hardness-greater than 555 VHN, multi hit capability of ultra high strength (UHS)/ ultra high hardness armour (UHHA) steel plate decreases, due to (i) low impact toughness, (ii) adiabatic shear band induced cracking (ASB) and (iii) susceptibility to plug formation[4-5]. Hence, the UHS/UHHA steels with quench and tempered martensite as primary microstructure have been developed with impact toughness more than 20 J for structural integrity against multi hit[6]. In most of the UHS/UHHA steels belonging to this category, high strength-toughness combination is derived from microstructure control by tempering of quenched steel. Carbide free nano-structured bainitic steel having high hardness (hardness 575-600 VHN) is a recent development in UHHA steels. It is noteworthy that hardness is not a measure of dynamic performance of the material against a particular threat and various ballistic test standards such as MIL-STD-46100; MIL-DTL-32332 and STANAG 4569 guides the designer to suitable thicknesses of materials for structural and appliqué armour applications.

Typically presence of coarse carbide particles in bainite acts as precursor to cracks and is not suitable for ballistic impact applications. However, off late, carbide free nano-structured bainite has emerged as potential armour candidate where suitable alloy design and processing schedules are adopted to engineer carbide free alternate films (nanometer in size) of austenite and bainite[7-8].

The alternate films of austenite and bainite are supposed to have high energy absorption capability[9]. High strength carbide free nano-structured bainite has been reported to have typical composition of Fe-0.8C-1.5Si-2Mn-1Cr-0.25Mo-1.5Co-1Al (all elements are in wt. %)[7-10]. High carbon content is chosen to generate a refined microstructure at low transformation temperature as low as 200 °C, whereas high silicon content is used to suppress carbide formation[7-14].

However, high carbon content has led to technological challenges of segregation, weld cracking and sluggish kinetics. Hence, recent trend is to develop lower carbon variant of lean bainitic alloy[15-17]. Further, limited data on ballistic impact studies and weldability of these classes of steels restricts the assessment of carbide free bainite vis-a-vis martensite based UHHA armour steels. To summarize major scientific gaps which are under exploration for adaptability of carbide free nano-structured bainitic steel as protective solution, are: (i) alloy design and suitable processing to enhance kinetics of bainite transformation, (ii) improvement in toughness by microstructure engineering, (iii) ballistic evaluation and design of add-on armour in comparison to martensite based UHHA steels and (iv) weld cracking susceptibility.

In this context, the present work is divided into three section, namely (i) alloy design aspects to engineer the

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microstructure of lean bainitic alloy which are being explored for better ballistic efficacy, (ii) ballistic tests to evaluate the ballistic performance of these alloys vis-a-vis UHHA steels and (iii) design criteria of add-on armour where by using suitable geometries, ballistic performance of armour steel plates can be enhanced. The newly developed material showed good weldability results and the same however, is out of scope of the present report.

2. ALLOY DESIGN

The strength of carbide free nano-structured bainite is deduced from two main aspects (i) finer microstructure consisting of large number of bainite-austenite interfaces (nanometre scale 50-100 nm in size) and (ii) stronger austenite which is richer in carbon content. The microstructure is engineered from the fact that the transformation temperature is very low to transform plastically stronger austenite into bainite at temperature just above martensite start temperature (M_s). However, the scale of the structure is limited by selection of transformation temperature above M_s which in turn is governed primarily by the carbon content of the alloy[7-8]. With increase in carbon content to 0.8 wt. % and above, M_s temperature is suppressed below 200˚C. However, progress of bainite transformation makes austenite richer in carbon content and further bainite has to transform from more stable austenite. The above mentioned mechanism not only limits the maximum bainite content in designed alloy system where limiting reaction is governed by locus of T_0 (Para-equilibrium) line but also makes the kinetics of transformation very sluggish. Thus, overall microstructure consists of nano films of austenite and bainite as well as untransformed blocky austenite. The high volume fraction of blocky austenite transforms into martensite during deformation and can act as untempered marteniste, lowering overall ductility/toughness of this class of alloys[13].

Nano-structured bainite with leaner carbon levels can overcome these challenges as mentioned above. With lowering carbon content three main goals were met (i) shifting of para-equillbrium boundary (T_o) towards further right, thus, increasing volume fraction of bainite, (ii) minimization of blocky austenite and (iii) faster kinetics of transformation. However, decrease in carbon content or increase in transformation temperature has negative impact on strength of bainite as increase in transformation temperature leads to coarser bainite as well as softer austenite. Hence, thermodynamic and kinetic calculations were done using ThermoCalc and JMATPRO to design low carbon (0.4-0.6 wt. %) lean bainitic alloy. It is also observed that without sacrificing strength, improvement in toughness can be achieved by using finer prior austenite grain size. Hence, vanadium was added as micro alloying addition, further, high Si content (of nearly 1.5 wt. %) was chosen to suppress carbide formation, Mn (0.5-2.0 wt. %) and Cr (0.5-2.0 wt. %) was selected based on hardenability, thermodynamic and kinetics criteria.

Table 1. Analysed chemical composition of steels

C	Si	Mn	Cr	Mo	V	S
0.4-0.6	1.5	0.5-2.0	0.5-2.0	0.25	0.2	<0.001

3. METHODOLOGY

3.1 Melting and Processing of the Alloy

The plates of bainitic steels were made by vacuum induction melting, homogenization, followed by hot forging and hot rolling. Typical alloy composition is mentioned in Table 1. The alloy was austenitised at 900 °C followed by austempering at 200-350 °C. The plates were received from ADD, South Korea in heat treated condition under Indo-South Korea Project agreement PA15-01 (2015).

3.2 Microstructure Characterisation

After heat treatment as well as impact experiments, cut cross section of the samples were polished using standard polishing methods. After polishing, mirror finish scratch free surface was etched with 2 % Nital (2 ml HNO_3 + 98 ml methanol) for microstructure studies. For transmission electron microscopy (TEM) studies of parent material, thin foils of around 0.5 mm were sliced using diamond wheel abrasive. The sliced sample was then reduced to a thickness of 100 microns by mechanical polishing. Then, the sample was further reduced in thickness by electrolytic (jet) polishing. The electrolyte used for this method was 90 % Acetic acid + 10 % perchloric acid. The lath thickness measurement from TEM bright field image was carried out using Olympus stream basic software. Lath thickness was measured using multiple images in order to ensure statistically meaningful results.

3.3 Mechanical Property Evaluation

Bulk Vickers hardness values were measured on mounted and polished cross section of the heat treated samples at 30 kg load using ASIAN make manually operated semi automatic bulk Vicker's hardness tester. Average of ten readings along with standard deviation is mentioned in the present study. The tensile tests of the material were carried out at a strain rate of 10^{-3} s^{-1}. Punch marks were made across the gauge length of the specimen. Elongation was determined by measuring displacement of the punch marks after the test. Standard Charpy V-notch (2 mm deep notch) specimens (10 mm × 10 mm × 55 mm size) were machined as per the ASTM standards and tests were carried out using the Tinius-Olsen impact testing instrument to find out the impact properties. Notch was made perpendicular to rolling direction. High strain rate compression of ARMOX 500 as well as nano-structured bainite was carried out a strain rate of 10^3 s^{-1} using Kolsky bar test set up. The details of the test procedure are described elsewhere[18].

3.4 Ballistic Tests

Ballistic efficiency of the material against particular ammunition can be evaluated by various test techniques in practice such as V_{50} as per MIL-STD-662F[19], depth of penetration[20-21] etc. V_{50} ballistic limit is defined as the average of an equal number of highest non-penetration (NP) velocities and complete penetration (CP) velocities which occur within a specified velocity spread. The method is intended to classify ballistic resistance of various armour materials[19]. MIL-46100 and MIL-32332 specified V_{50} values for materials of defined thickness having hardness less and higher than 575 VHN respectively by testing as per MIL-STD-662F, at 30° obliquity.

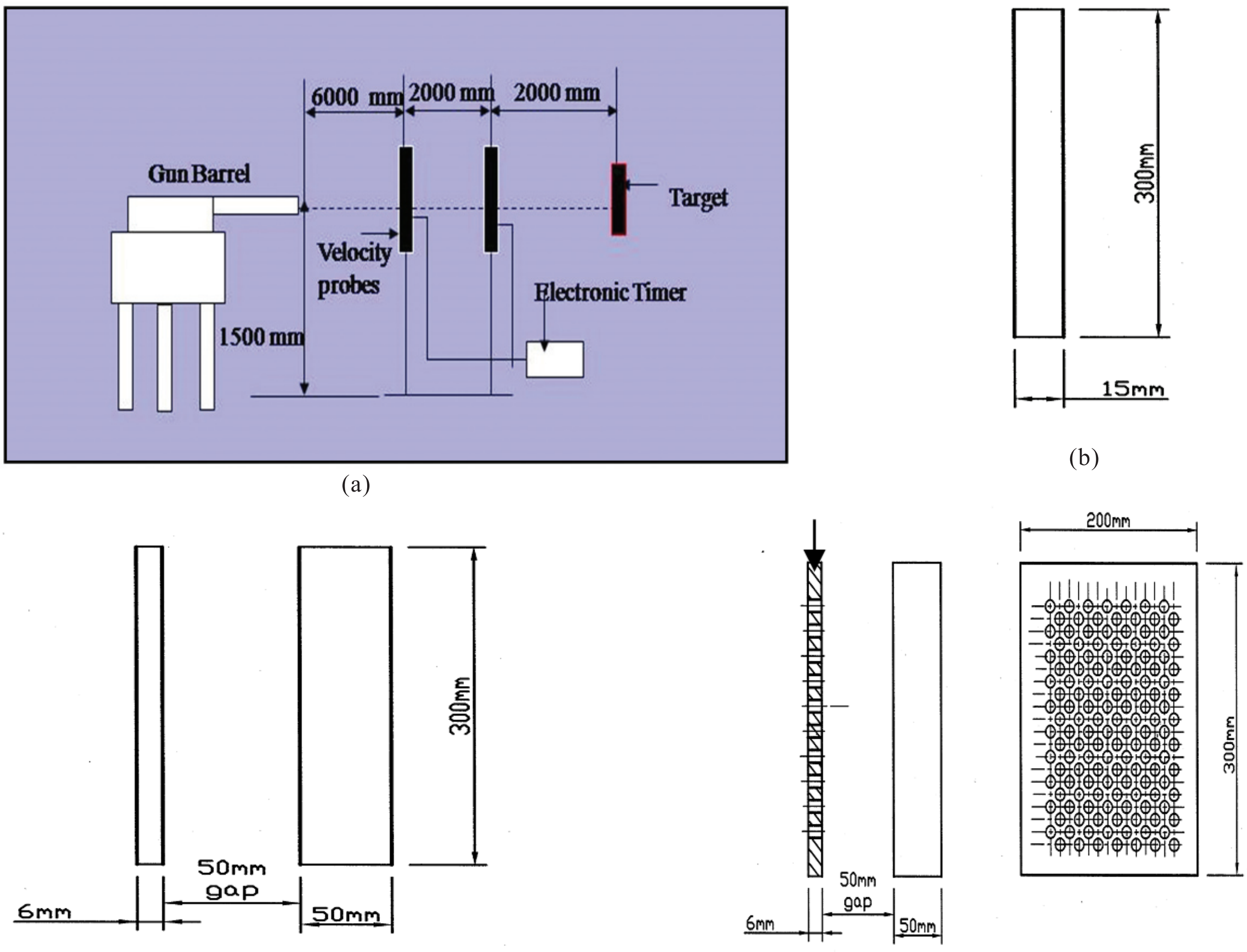

Figure 1. (a) Schematic of the ballistic test set up, (b)-(d) schematics of various target configurations used namely (b) monolithic plate, (c) non perforated and (d) perforated assembly showing side view of the assembly and front view of perforated plate respectively.

The velocity is varied by varying explosive charge mass of the projectile. The average of velocities for NP and CP is taken as V_{50} values as per MIL-STD-662F. Depth of penetration (DOP) test uses changes in depth of penetration in a semi-infinite target with respect to standard rolled homogeneous armour (RHA) steel[20-21] against a particular threat. In case of thin plates change in reference depth of penetration of a semi-infinite witness plate is taken into consideration for measurement of performance[21].

In the present study these tests can be categorized as following: (i) V_{50} tests on 6 mm thick nano-structured bainite against 7.62 AP projectile, (ii) V_{50} tests on 15 mm thick nano-structured bainite against 12.7 AP projectile, (iii) DOP tests on semi-infinite monolithic thick (15 mm thick) of nano-structured bainite and ARMOX 500 and (iv) DOP on witness Al-alloy plates used in conjunction with front nano-structured bainite and ARMOX plates (with and without perforated geometries) against 7.62 AP projectiles. Ballistic evaluation of perforated vs. non-perforated plates were carried out to find out reduction in DOP in backing Al-alloy plate due to perforations geometry. In all these tests, 50 mm thick witness Al-alloy plate of size 300 mm x 200 mm was used as backing at a distance of 50 mm from the front plate by using spacers. Thus, an air gap of 50 mm was maintained between front steel plates and backing witness plate. 7.62 AP as well as 12.7 AP projectiles is ogive shape hard steel core projectiles. The hardness of tip of the projectile of 7.62 AP is around 800-900 VHN. The core diameter of these projectiles is 6.1 mm and 10.5 mm respectively. The length of the core of projectile is 28.1 mm and 52.7 mm respectively. The weight of projectile core of 7.62 AP and 12.7 AP is 5.4 gm and 29.86 gm respectively. The muzzle velocity of both ammunition using universal gun is around 850 ±10 m/s. The charge mass was varied for v_{50} experiments to obtain a range of velocities. Further, details of the projectiles are mentioned elsewhere[22-23]. The schematic of the ballistic test set up (Fig. 1(a)) along with various test configurations is shown in Fig. 1.

Figure 1 shows three type of targets tested in the present configuration namely solid monolithic alloy (Fig. 1(b)), presented by solid rectangle), non-perforated configuration

(Fig. 1(c)), solid plate placed along with witness Al-alloy block) and perforated configuration (Fig. 1(d)), perforated plate placed along with witness Al-alloy block). A minimum of six shots were fired on each plate at a velocity of 850 ± 10 m/s. Targets were fixed on a stand at a distance of 10 meters. Ballistic tests were conducted at normal angle of attack. It is to be noted that ballistic efficiency of newly developed carbide free nanobainitic steel is compared with reference high hardness ARMOX 500 steel having predominantly martensite as microstructure constituent.

4. RESULTS AND DISCUSSION

4.1 Microstructure

The mechanism of bainite transformation is based on the principles of an individual platelet growing without diffusion and excess carbon then getting partitioned into residual austenite. The limiting fraction of bainite at any temperature is determined by the condition that the free energies of austenite and ferrite of the same composition become identical. Thus, time of completion of bainite transformation depends upon alloy composition, isothermal holding temperature and carbon partitioning between bainitic ferrite and austenite. The time for completion of bainite transformation in the present study was estimated based on hardness values and optical microstructure studies. The bainite, because of its nano structure and possible carbide content (if any), etches faster and appear in dark contrast compared to the martensite. Hence, with progress of deformation significant microstructure changes will be noticed. Also, as progress of transformation nears completion, hardness values tend to saturate.

Optical microstructure of nanobainitic alloy having transformation time of 0.5 h, indicating absence of blocky austenite as well completion of bainite transformation is shown in Fig. 2(a). Figure 2(b) shows representative transmission electron micrographs of the alloy indicating austenite (γ) and bainite (α_b) with lath widths in the range of 150-200 nm. The overall retained austenite content measured from X-ray diffraction studies is less than 10 % in the presently studied alloy. However details of X-ray diffraction studies is beyond the scope of the reported study and hence, is not elaborated here.

4.2 Mechanical Properties

Table 2 shows yield strength (YS), ultimate tensile strength (UTS), % elongation and Charpy impact toughness values evaluated at room temperature of the nano-structured bainitic alloy. A comparison is also shown with mechanical properties of typical high carbon nanobainitic steel and ARMOX 500 steel. The nano-structured bainite shows optimum combination of strength-toughness combination having strength more than 2.0 GPa and impact toughness of more than 20 J. The difference in mechanical properties with earlier reported nano-structured bainite[1-4] may be attributed to following factors: (i) fraction of retained austenite, bainite, martensite phase (if any), (ii) morphology of retained austenite like blocky v/s film austenite, (iii) composition of austenite and bainite phases, (iv) stability of retained austenite and (v) size and distribution of austenite and bainite phases.

Flow behaviour of ARMOX as well as nanobainite was evaluated at high strain rates typical of impact loading conditions using Kolsky bar test set up. True stress-strain curves of ARMOX 500 steel and nano-structured bainite at a strain rate of 5.6 x10^3 s^{-1} is shown in Fig. 3. The nano-structured

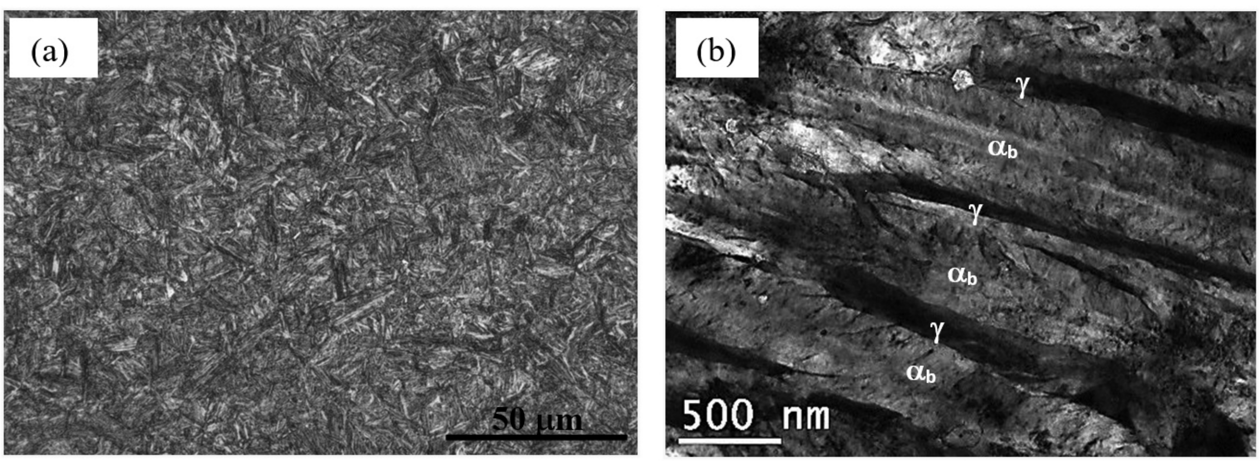

Figure 2. (a) Optical microstructure and (b) Transmission electron micrograph of nano-structured bainite.

Table 2. Mechanical properties of studied nano-structured bainite (**), ARMOX 500. A comparison is also shown of the mechanical properties of studied nano-structured bainite (**) with literature data (***).

Material	Hardness (VHN)	Y.S (MPa)	U.T.S (MPa)	El. (%)	Impact energy* (J)
Nano-structured bainite**	600 ± 10	1450 ± 20	2050 ± 12	15 ± 1	23 ± 2
Nanobain***	600	1500-1800	2000-2200	5-10	4-7
ARMOX 500	538	1449	1844	11	35

*Impact energy evaluated at room temperature, **present study, ***Nanobain[7,10-11].

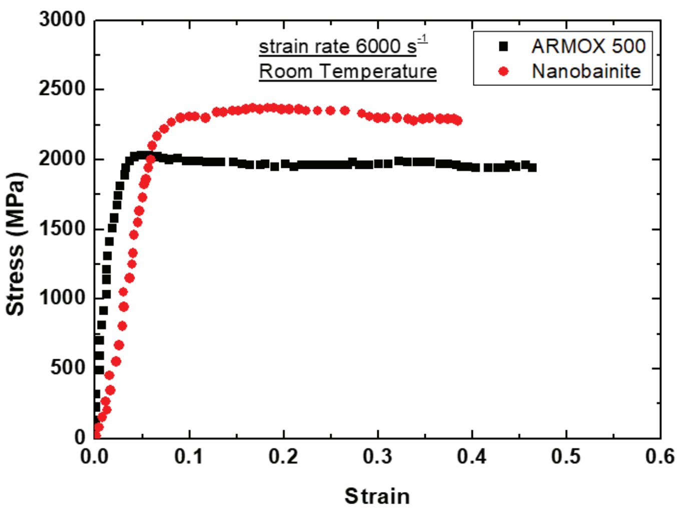

Figure 3. High strain rate flow curves of ARMOX 500 and nano-structured bainite.

bainite shows high strength and limited work hardening at high strain rates. However, nano-structured bainite has higher work hardening than that of ARMOX at high strain rates. Various earlier works on high strain rate deformation of nano-structured bainite shows TRIP effect. The TRIP effect and corresponding energy absorption causing austenite to martensite transformation during high rate loading may be responsible for higher work hardening in nano-structured bainite compared to ARMOX steel[9, 24]. With increase in strain rate, change in deformation induced microstructure, twinning and localisation of deformation in form of adiabatic shear bands are typical microstructure details which affects strain hardening in this class of materials at higher rates of loading[9, 24].

4.3 Ballistic Impact Studies

4.3.1 Ballistic Evaluation of Monolithic Plates Using V50 Test Method

The ballistically tested plates of carbide free nano-structured bainitic alloy against 7.62 mm AP and 12.7 mm AP projectiles is shown in Fig. 4. The plate is intact after testing and there are no cracks observed. Table 3 summarizes the V_{50} evaluation on these plates impacted against 7.62 AP and 12.7 AP projectiles as per MIL-STD-662F. The V_{50} velocity has been calculated by taking average of the highest velocity that completely stop the projectile and the lowest velocity that gives complete penetration. The V_{50} is found to be equivalent or superior to existing UHHA as per MIL-46100 and equivalent to MIL-32332. Under ballistic impact condition against 7.62AP projectiles, the austenite films as well as blocky morphology may transform to martensite leading to transformation induced plasticity (TRIP) effect. Thus, phase transformation contributes to partial energy absorption during ballistic impact is one of the primary factor which leads to higher V_{50} of nanobainitic steel

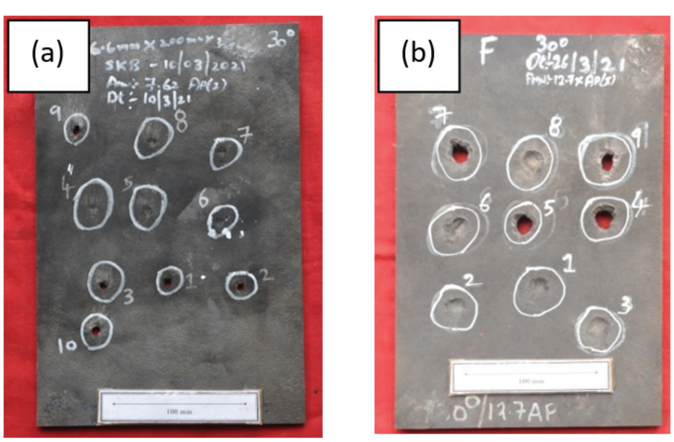

Figure 4. Front face of nanobainitic steel against: (a) 7.62 AP and (b) 12.7 AP projectiles respectively using V_{50} test method.

Table 3. V_{50} results of nanobainitic steel plates as well as the same as per MIL-STDS

Material	Thickness (mm)	Projectile	V_{50} (m/s)
Nano-structured bainite	6.1	7.62 AP	733
	15 mm	12.7 AP	838
MIL-46100	6.1	7.62 AP	648
	15.1	12.7 AP	815
MIL-32332	6.1	7.62 AP	734
	15.1	12.7 AP	870

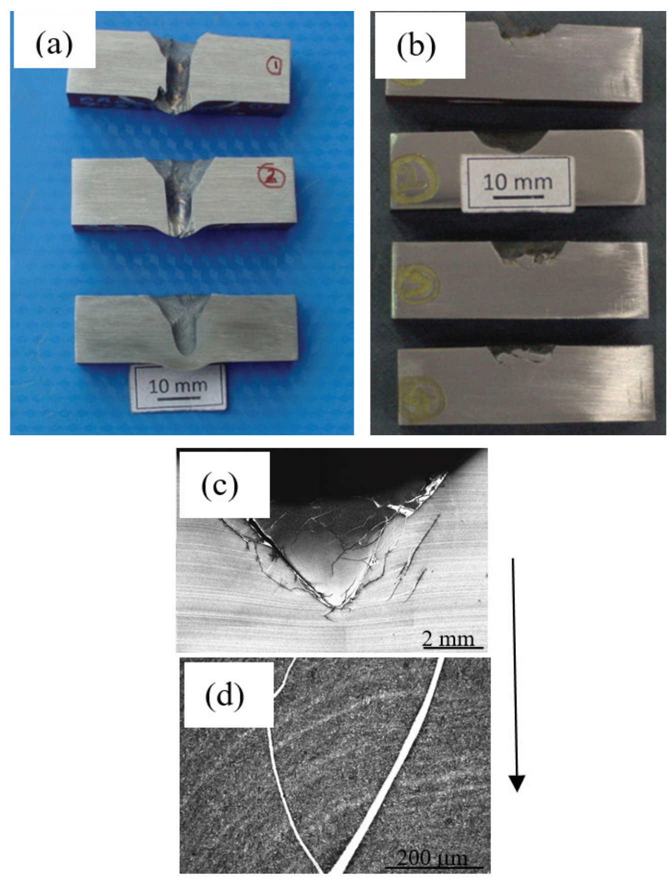

Figure 5. Penetration channels of: (a) ARMOX 500 and (b) nano-structured bainitic steel plates impacted against 7.62AP projectile at an impact velocity of 850 m/s, (c) magnified view of impact crater area and (d) microstructure of one of such representative crater of nano-structured bainitic alloy. The arrow shows projectile impact direction.

than that of UHHA against 7.62 AP projectiles as mentioned by V_{50} values as per MIL-STDS.

4.3.2 Ballistic Evaluation of Monolithic Plates Using DOP Test Method

Figure 5 (a)-(b) shows the penetration channel in 15 mm thick martensite based ultra high strength steels ARMOX 500 and carbide free nano-structured bainitic steel plates respectively when impacted against 7.62 mm AP projectile at impact velocity of 850 ± 10 m/s and at normal angle of impact. It is to be noted that 15 mm thick ARMOX 500 steel plate when tested against 7.62 mm AP projectile shows complete penetration, whereas nano-structured bainitic steel plate shows multi-hit capability without any substantial depth of penetration as shown in Fig. 5 (b)-(c). The lower thickness (11 mm and 13 mm) plate shows perforations. Thus, ballistic performance of carbide free nanobainitic steel plate suggests complete protection against 7.62 AP projectiles at an areal density of nearly 120 kgm^{-2}.

The higher performance of nano-structured bainite is due to superior mechanical properties at low as well as at high strain rates. Figure 5 (d) shows the microstructure of ballistic impact crater half of 15 mm thick high hardness carbide free nanobainitic steel when tested against 7.62 AP projectiles using DOP test method. It can be clearly seen that high strength and impact resistance by the alloy is efficient enough to break the projectile. ASB induced cracks are seen in the local region near the crater. With further decrease in thickness, the stresses generated in the projectile is high enough to reach critical strain to failure under high strain rate conditions and hence, complete perforation is observed in 13 mm thick plates. ASB induced cracking and plug formation are also the prominent features seen in various ultra high strength steels and is attributed to domination of thermal softening over strain and strain rate hardening. The impact energy dissipation is a local phenomenon in various ultra high strength steels leading to sharp increase in strain, strain rate and temperature during the projectile-target interaction which eventually leads to ASB induced crack formation.

4.3.3 Ballistic Efficiency of Facing Perforated Plate

Ballistic efficiency of monolithic high hardness plates can be improved by suitable geometrical designs. Perforated armours mounted on base plate armour are one of the widely used add-on armours which increase ballistic efficiency significantly. Based on numerical simulations[25-28], perforated geometries were designed on ARMOX 500 and carbide free nano-structured bainitic steel plates.

To understand the material effect perforated geometries on front plate, thicknesses of front as well as backing plate and air gap between them were kept similar. A comparison was made by measuring average depth of penetration in backing reference Al-alloy plate in all these three plates with and without perforation geometries. Figure 6 (a)-(b) show the depth of penetration observed in reference Al-alloy when ARMOX 500 was used as front plate with and without perforated geometry. It can be clearly seen that depth of penetration in backing Al-alloy plate is reduced by nearly 50 % (from ~28 mm to ~14 mm) by using front perforated configurations. In case of nano-structured bainitic alloy the least DOP is observed in backing Al-alloy and is nearly 14 mm, which decreases significantly nearly 30 % (from ~ 14 mm to ~ 8 mm) due to use of front perforated configurations (Fig. 6 (c)-(d)). Ballistic test results of front perforated ARMOX 500 and nanobainitic perforated steel plate v/s non-perforated plates are summarized in Table 4.

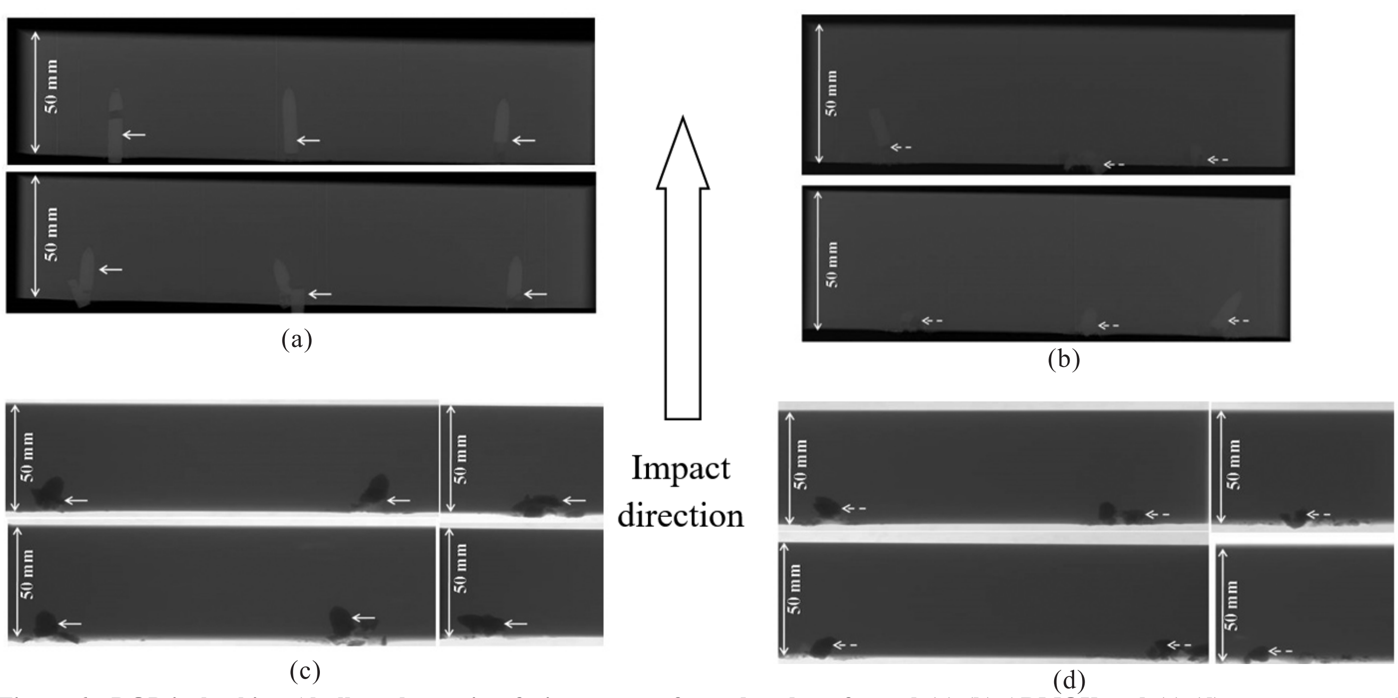

Figure 6. DOP in backing Al-alloy plate using facing non perforated and perforated (a)-(b) ARMOX and (c)-(d) nano-structured bainite respectively. (a) & (c) non perforated configuration, (b) & (d) perforated configurations.

Table 4. Ballistic performance evaluation of perforated v/s non-perforated ARMOX 500 and nano-structured bainitic steel. DOP is measured in reference backing Al-alloy plates

Front plate	Front plate thickness (mm)	Air gap (mm)	Thickness of backing Al-6061 alloy plate (mm)	Velocity (m/s)	Average DOP in backing plate (mm)
NPF ARMOX	6.0	50	50	835	24.9
PF ARMOX	6.0	50	50	840	12.5
NPF- nanobainitic	6.0	50	50	838	13.4
PF- nanobainitic	6.0	50	50	839	8.5

Note: PF: perforated and NPF: Non perforated assembly as shown in schematic figure 1 (b).

It is clear from these results that perforations have significant effect on improving ballistic performance. Perforated bainitic steel shows least depth of penetration in the backing plate and has superior performance out of all combinations. The effect of perforation geometries in improving ballistic performance has been detailed in various earlier studies[25-28] and can be summarized as (i) generation of high stresses on projectile during interaction with edge of perforation, leading breakage of projectile, (ii) bending stresses induced in a projectile when it interacts with perforation or edge of the plate such as periphery of the perforation and (iii) deviation of the projectile from its normal path. Thus, incoming kinetic energy is dissipated and significant decrease in depth of penetration is observed. It is also noticeable that with change in material properties of front perforated plate, the ballistic performance changes due to influence on above mentioned phenomenon. Based on these results armour module designs with various front plate and backing plate configurations were simulated and experimentally validated.

5. CONCLUSIONS

- The alloy design and processing cycle of newly designed nano-structured bainitic alloy resulted into bainite transformation completion time of around 0.5 h. The microstructure of nano-structured bainite alloy is dominantly alternate layer of bainitic ferrite and austenite
- A very high strength more than 2.0 GPa and impact toughness of nearly 20 J was obtained in nanobainitic alloy
- The ballistic performance measured by V_{50} as well as by depth of penetration test method shows nano-structured bainite has ballistic efficiency superior or equivalent to MIL-46100 and MIL-32332
- Ballistic test results of front perforated steel plate v/s non-perforated plates showed that nearly 50 % reduction in depth of penetration in reference backing Al-alloy plate can be achieved using perforated configurations in front plate
- Perforated armour modules shows multi hit protection against 7.62AP projectiles at nearly 30-40 % less weight when compared to monolithic plates.

REFERENCES

1. US Military specifications, MIL-A-12560 H (MR), amendment, armour plate, steel, wrought, homogeneous. 2000.
2. U.S. Military specification, MIL-A-46100 (DMR), armour plate, steel, wrought, high hardness.1988.
3. Showalter, D.D.; Gooch, W.A.; Burkins, M.S.; Thorn, V.; Cimpoeru, S.J. & Barnet, R. Ballistic testing of Australian Bisalloy steel for armour applications, USA, Army Research Laboratory,Technical Report No. TR-ARL-RP-181. 2007.
4. Woodward, R.L.The interaction of failure modes observed in the penetration of metallic targets. *Int. J. Impact Eng.*, 1984, 121-129.
5. Manganello, J. & Abbott, K.H. Metallurgical factors affecting the ballistic behaviour of steel targets. *J. Mater.*,1972,**7**, 231-239.
6. Crouch, I.G. The science of armour materials. Woodhead publishing and materials, UK , 2007.
7. Bhadeshia, H.K.D.H. Bainitic bulk-nanocrystalline steel. Third Int. Conference on Advanced Structural Steels, Gyeongju, South Korea, 2006
8. Huang,H.;Sherif,M.Y.&Rivera-Dı´az-del-Castillo, P.D.E.J. Combinatorial optimization of carbide-free bainitic nanostructures. *Acta Mater.*, 2013, **61**, 1639-1647.
9. Tsai, Y.T.; Lin, C.R.; Lee, W.S.; Huang, C.Y. & Yang, J.R. Mechanical behavior and microstructural evolution of nanostructured bainite under high strain rate deformation of Hopkinson bar. *Scrip. Mater.*, 2016, **115**, 46-51.
10. Mateo, C.G.; Caballero, F.G. & Bhadeshia, H.K.D.H. Mechanical properties of low temperature bainite. *Mater. Sci. Forum.*, 2005, 500-501, 495-502.
11. Peet, M.J.; Fielding, L.C.D.; Hamedany, A.A.; Rawson, M.; Hill, P. & Bhadeshia, H.K.D.H. Strength and toughness of clean nanostructured bainite. *Mater. Sci. Tec.*, 2016, **33**(10), 1171-1179.
12. Christopher Neil Hulme-Smith. University of Cambridge, UK, 2016. (Ph.D Thesis)
13. Morales-Rivas, L.; Garcia-Mateo, C.; Sourmail, T.; Kuntz, M.; Rementaria, R. & Caballero, F.G. Ductility of Nanostructured Bainite. *Metals.*, 2006, **6**, 392.
14. Jiang, T.; Liu, H.; Sun, J.; Guo, S. & Liu, Y. Effect of austenite grain size on transformation of nano-structured bainite and its mechanical properties. *Mater. Sci. Eng. A*, 2016, **666**, 207–213.
15. Garbarz, B.; Marcisz, J.; Burian, W. & Zelaza, I.M. Technological peculiarities of manufacturing nanobainitic steel plates. *Düsseldorf*, 2015, 15–19.
16. Sourmail, T.; Smanio, V.; Ziegler, C.; Heuer, V.; Kuntz, M.; Caballero, F.G.; Garcia-Mateo, C.; Cornide, J.; Elvira,

R.; Leiro, A. & Vuorinen, E. Novel nanostructured bainitic steel grades to answer the need for high-performance steel components (Nanobain). Research Fund for Coal and Steel Publications, European Commission. 2013.
17. Garcia-Mateo, C.; Caballero, F.G.; Sourmail, T.; Smanio, V. & Garcıa de Andres, C. Industrialized nanocrystalline nanobainitic steel. Design approach. *Int. J. Mater. Res.*, 2014, **105**, 725-734.
18. Rajaraman, S.; Jonnalagadda, K.N. & Ghosh, P. (eds.), Indentation and dynamic compression experiments on microcrystalline and nanocrystalline nickel. dynamic behaviour of materials, Proceedings of the 2012 annual conference on Experimental and Applied Mechanics, New York, 2013.
19. MIL-662F, V50 ballistic test for armour, Department of defence USA, Test method standard, December 1997.
20. Rosenberg, Z.; Yeshurun, Y.; Bless, S.J. & Okajima, K. A new definition of ballistic efficiency of brittle materials based on the use of thick backing plates', in 'Impact loading and dynamic behaviour of materials', (ed. C. Y. Chiem et al.), Oberursel, DGM Informations gesellschaft mbH, 1988, 491–498.
21. Franzen, R.R; Orphal, D.L. & Anderson Jr, C.E. The influence of experimental design on depth-of-penetration (DOP) test results and derived ballistic efficiencies. *Int. J. Impact Eng*., 1997, 727-737.
22. Mishra, B; Jena, P.K.; Ramakrishna, B.; Madhu, V.; Bhat, T.B. & Gupta, N.K. Effect of tempering temperature, plate thickness and presence of holes on ballistic impact behavior and ASB formation of a high strength steel. I*nt. J. Impact Eng.*, 2012, **44**, 17-28
23. Ramakrishna, B.; Mishra, B.; Madhu, V. & Bhat, T.B. An experimental and numerical study of edge impact of 7.62 mm AP projectile on perforated armour high hardness steel plates. Indo-Russian workshop on Topical problems on solid mechanics, BIT campus Goa, India, 2008.
24. Marcisz, J.; Garbarz, B. & Janiszewski, J. Changes in mechanical properties of ultrahigh strength nanostructured steel resulting from repeated high strain rate deformation. *Problemy Mechatroniki.*, 2019, **10** , 99-120.
25. Kilic, N.; Bedir, S.; Erdik, A.; Ekici, B.; Tasdemirci, A. & Guden, M. Ballistic behavior of high hardness perforated armor plates against 7.62 mm. *Mater. Design.*, 2014, **63**, 427-438.,
26. Kilic, N.; Ekici, B. & Bedir, S. Optimization of high hardness perforated steel armor plates using finite element and response surface method. *Mechanics Adv. Mater. Structures.*, 2016.
doi: 10.1080/15376494.2016.1196771.
27. Balos, S.; Howard, D.; Brezulianu, A. & Zlatanovic, D.L. Perforated plate for ballistic protection- a review. *Metals.*, 2021, **526**, 1-18.
28. Fras, T.; Murzyn, A. & Pawlowski, P. Defeat mechanism provided by slotted add-on bainitic plates against small caliber 7.62 mm x 51 AP projectiles. *Int. J. Impact Eng.*, 2017, **103**, 241-253.

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