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Aluminium Nanoparticles: The Potentials of Metalized Explosives with Combined Destructive Effect (Combustion/Detonation)

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Aluminium Nanoparticles: The Potentials of Metalized Explosives with Combined Destructive Effect (Combustion/Detonation)

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Abstract. Even though, reactive metal particles can boost the energy density of explosive materials. Such particles will react behind the detonation wave front with decrease in detonation velocity and brisance (destructive effect). This study reports on the effective development of aluminium nanoparticles (NPS) of 100 nm particle size. Al NPs offered superior performance compared micron scale particles. Al NPs offered an increase in shock wave strength by 48 % compared with 17 % for micron scale particles. While micron-Al decreased the destructive effect of TNT by -6.5 %; Al NPs offered an increase in destructive effect by 21 %. The main outcome of this study is that Al NPs offered an enhanced detonation velocity of 6330 m/s compared with 5650 m/s for TNT. Additionally Al NPs offered decrease in TNT critical diameter from 40 mm to 20 mm. While conventional Al particles could act as desensitizer; Al NPs could act as sensitizer and could combust efficiently within detonation wave front. This study reports on the real development of metalized nano-composite explosives with combined destructive effect (combustion/detonation).

Keywords: Metalized explosives; Combustion, Destructive effect; Workability; Brisance; Thermal behaviour.

1. Introduction

The energy density of common energetic compounds is quite low; as it is limited by their enthalpy of formation. Higher energy density can be achieved through integration of reactive metal particles figure 1 [1].

Aluminium particles with combustion heat of 32000 J/g; is the common high energy density material [1-3]. Reactive metal fuels (i.e. Al) could offer a longer duration pressure pulse figure 2 [4].

In general, the long ignition delays and slow combustion rates could contribute behind detonation wave front. This action could decrease the detonation velocity [5]. Consequently reactive metal particles could transfer ideal detonation into non-ideal. This could limit the capability of producing sharp pressure pulses required for many applications. Furthermore, aluminium particles are covered with protective oxide layer; that could hinder the rapid combustion process [6].

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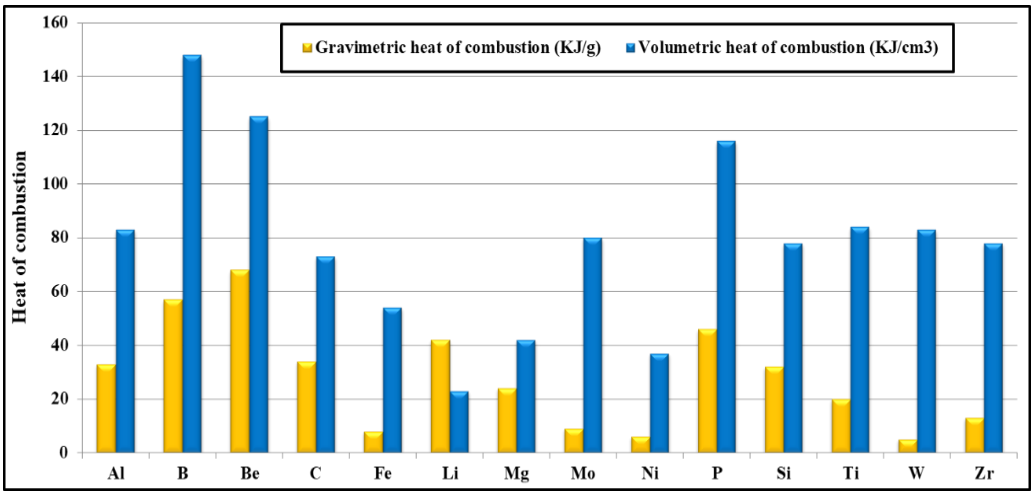

Figure 1. Heat output for common reactive fuels (Gravimetric and Volumetric).

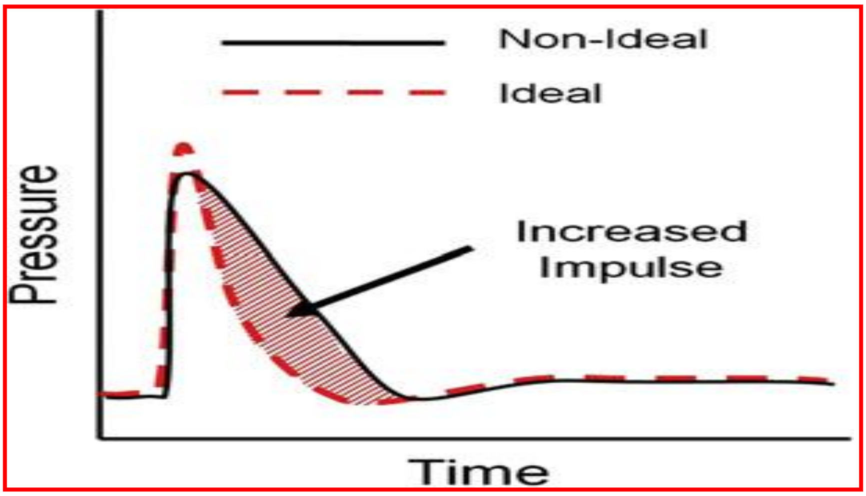

Figure 2. Pressure-time profile for an ideal vs. non-ideal detonation reaction.

Oxide layer should be pealed out for reactive metal core to combust with free oxygen. Aluminium combustion consists of two main stages including ignition and quasi-steady burning. The ignition of aluminium particles begins with a relatively short heterogeneous surface reaction (HSR) stage (Figure 3-a) and quickly transitions to a quasi-steady diffusion flame figure 3-b [7]. During the ignition phase, the particle heats up from convection and volumetric compression to its melting temperature; the short lived HSR stage consisting of solid metal (m_s) and liquid metal (m_l) surrounded by a layer of metal oxide (m_{mox}). Upon heating from convection and volumetric compression, the particle temperature increases until a melting phase transition occurs [5-8].

At sufficiently high temperature and mechanical loading, the particle oxide layer peels back allowing for molten aluminium to evaporate and form a diffusion flame [7-11]. This combustion mechanism confirmed that metal particles could react over longer timescale than the detonation of explosive material. Hence metal particles could induce non-ideal detonation [12-19].

For ideal detonation reaction, all potential energy of the explosive is liberated almost instantly in a thin reaction zone prior to C-J plane; behind the C-J plane are stable detonation products (Figure 4-a) [20-22]. In non-ideal detonation, the potential energy is not liberated completely within reaction zone; significant degree of chemical reactions take place behind the C-J plane figure 4-b [20-25].

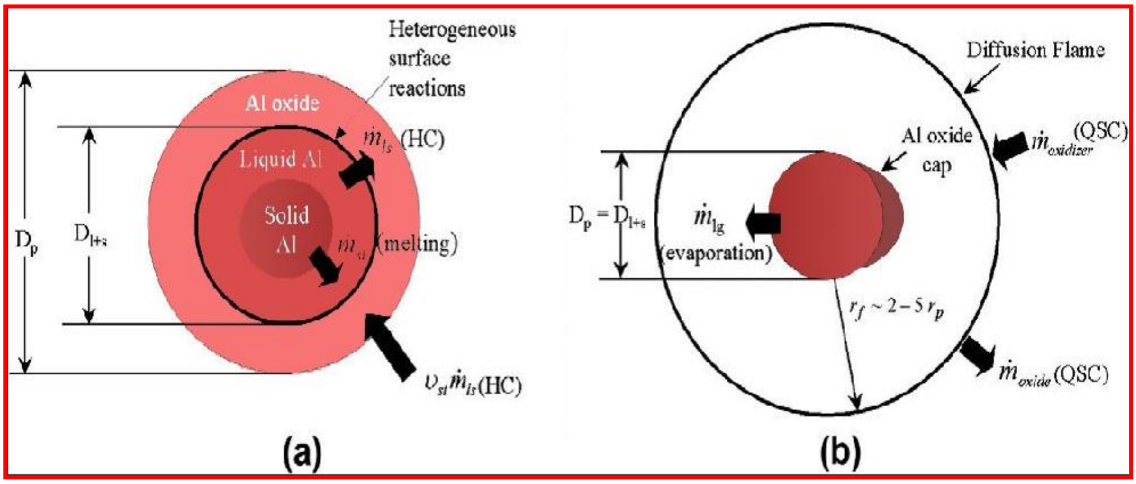

Figure 3. Sketch combustion model of aluminium particles.

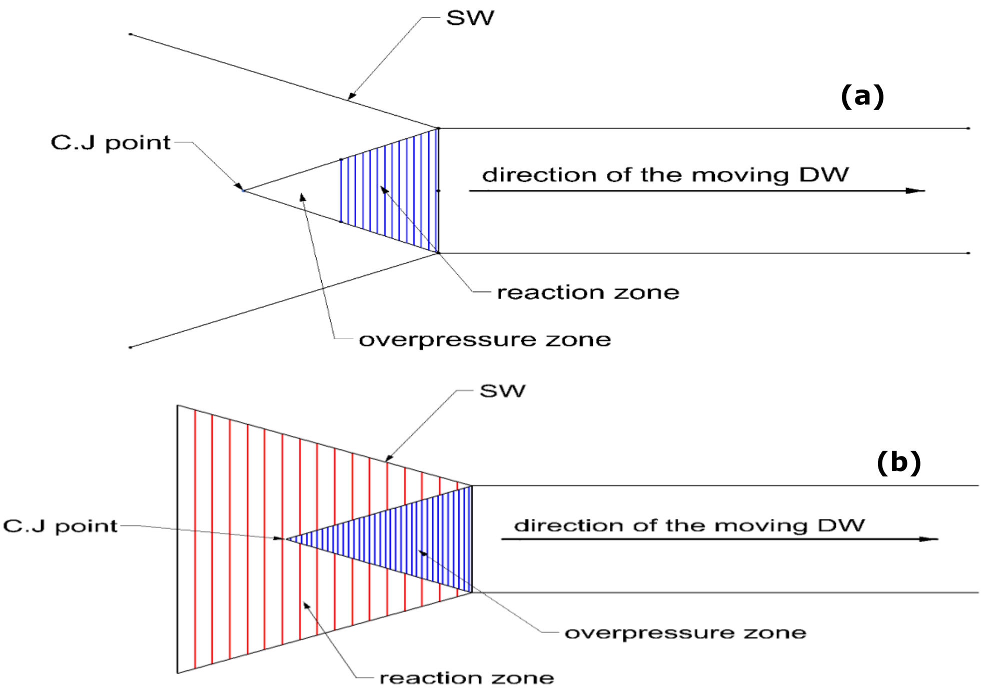

Figure 4. Schematic for ideal detonation reaction (a), and non-ideal detonation reaction (b).

Though aluminium could support the shock front via the energy released in the primary reaction zone; aluminized explosive offered non-ideal detonation with decrease in detonation velocity [26]. The reaction zone length for metalized explosives was reported to be more than two times that for organic explosives [26]. While conventional Al particles could contribute only to the work done by the expanding combustion products; they could reduce the destructive effect of explosive material [27-33].

Aluminized explosives are non-ideal, with long sequential reaction zones that depend on particle size [25]. It was presumed that fine Al particles are consumed more rapidly in the CHNO reaction

IOP Conf. Series: Materials Science and Engineering **975** (2020) 012009 doi:10.1088/1757-899X/975/1/012009

zone compared to larger particles [2]. Recently, aluminized explosive formulations employing fine aluminium particles were developed to produce high initial detonation temperatures, pressures, and velocities [5, 30]. They can offer both excellent early volume expansion metal pushing and high expansion blast capabilities [30-31]. The great impetus of nanotechnology is the massive increase of the surface area/weight [27-29].
Colloidal Al NPs were developed via wet milling. Al NPs offered superior performance compared with conventional Al particles. Al NPs offered an increase in workability of TNT by 48 % using ballistic mortar test, compared with 17 % for micron size particles. While micron-scale particles decreased the destructive effect of TNT by -6.5 %; Al NPs offered an increase in destructive effect of TNT by 21 % using kast test and Hess test. Nano-scale Al particles could combust more efficiently within the detonation wave front. Detonation velocity measurements confirmed that Al NPs offered enhanced detonation velocity and lower critical diameter.

2. Materials and methods

2.1 Chemicals and reagents
Industrial aluminium particles 10 µm were purchased from Alpha chemika.. Isopropyl alcohol (IPA) was employed as dispersing medium of reactive metal particles; IPA was purchased from Sigma-Aldrich. All chemicals were used as received.

2.2 Characterization of aluminium particles
The particle size of aluminium particles was visualized using scanning electron microscope SEM, Zeiss EVO-10 by Carl Zeiss Corporation. The crystalline phase was investigated with X-ray diffraction (XRD) D8 advance by Burker Corporation over the angle range 2θ from 5 to 65 degrees.

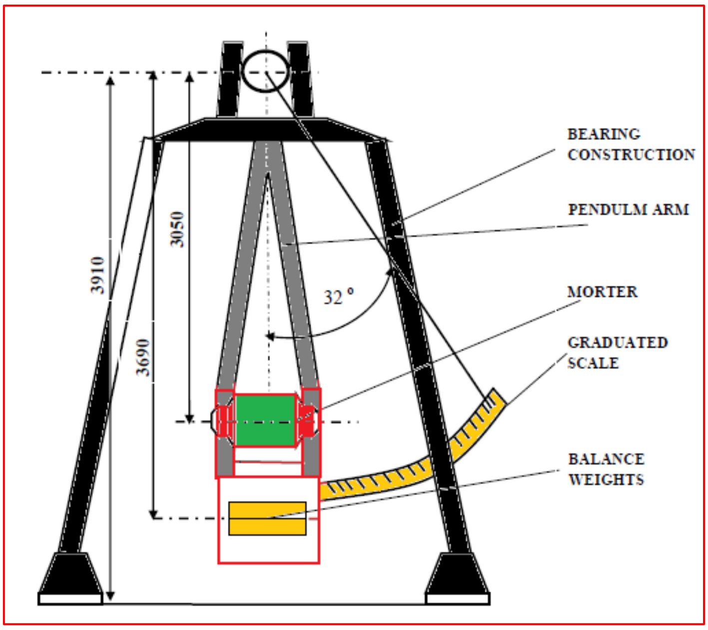

Figure 5. Schematic diagram of ballistic mortar [19]

2.3 Integration of metallic fuels particles into energetic matrix
It is widely accepted that enhanced dispersion characteristics can be accomplished via integration of colloidal particles into energetic. Ultrasonic probe homogenizer was employed to disperse Al NPs in IPA, to break down any aggregates. Colloidal Al particles were integrated into molten TNT.

IOP Conf. Series: Materials Science and Engineering **975** (2020) 012009 doi:10.1088/1757-899X/975/1/012009

2.4 Workability evaluation

Workability in terms of shock wave strength was evaluated using Ballistic mortar test. Ballistic mortar composed of suspended massive steel mortar figure 5. Upon exploding standard charge (10 g) within the mortar cavity, the maximum mortar displacement was recorded. Mortar displacement is function of detonation overpressure. Consequently, the equivalent overpressure value was evaluated using standard charts.

2.5 Explosive strength evaluation

The impact of Al particles on TNT brisance was evaluated using Kast test developed by PHYWE (Germany). Destructive effect evaluation was conducted via measurement of copper crusher compression figure 6.

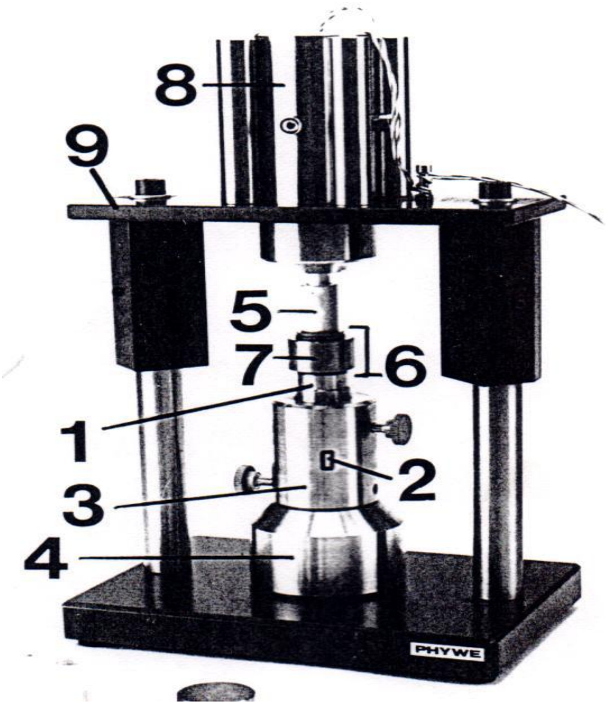

Figure 6. Schematic for destructive effect using Kast test [19].

Moving steel cylinder (1) transmitted the overpressure to copper crusher (2). The copper crusher height was precisely measured, upon exploding explosive charge (2 g).

2.6 Destructive effect by Hess test

The brisance of an explosive was evaluated on the basis of the compression of a lead cylinder under the action of the shock wave of standard explosive charge. Lead cylinder compression is proportional to the destructive effect of an explosive charge figure 7.

The difference in the lead cylinder height would act as a direct measure of the brisance of the tested explosive formulation relative to TNT.

2.7 Detonation velocity measurement

The impact of Al particle size on detonation velocity of TNT was evaluated using Exploment-Fo-Multi channel, by Kontiniro A. G. (Swiss made). The time interval for detonation wave to travel between two points (start and end) was measured using an electronic counter figure 8.

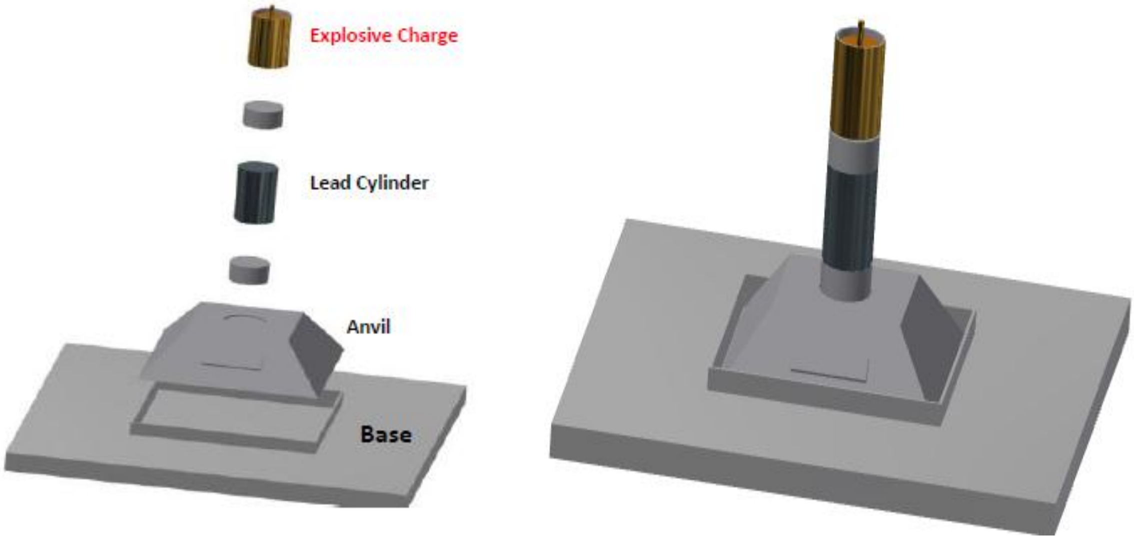

Figure 7. Setup for the determination of destructive effect by Hess test [9]

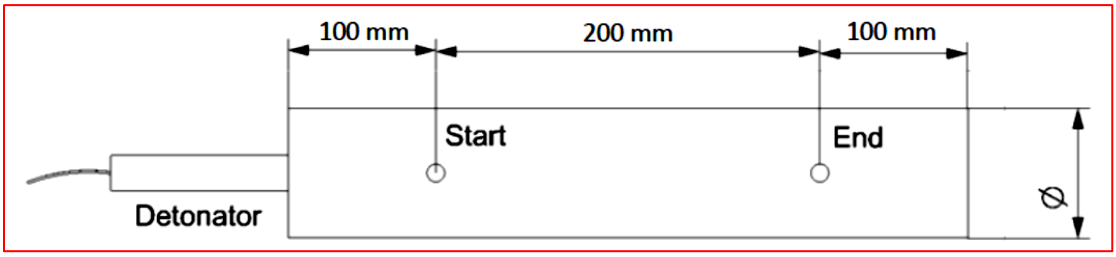

Figure 8. Detonation velocity measurement using an electronic timer

3. Results and discussions

3.1 Characterization of Al particles

The morphology of employed aluminium particles was investigated with SEM. Al particles in the shape of spheres with 10 µm average particle size were reported from SEM micrograph figure 9-a. The particles size of employed Al NPs was investigated with TEM. TEM micrographs demonstrated Al particles in the shape of flakes with average particle size of 100 nm figure 9-b.

3.2 Workability evaluation

Under the action of the detonation products, the mortar was moved from its equilibrium position. The maximum displacement was recorded. This movement can represent the workability of the tested explosive material figure 10.

Whereas micron-Al particles demonstrated an increase in TNT workability by 17 %; Al NPs offered an increase in TNT workability by 48 %. This enhanced performance was ascribed to the fact that Al NPs could vaporize easily and combust efficiently within the detonation wave front. Excess Al NPs could contribute to the shock wave strength and could combust more efficiently with oxygen in the air adding substantial heat output [25].

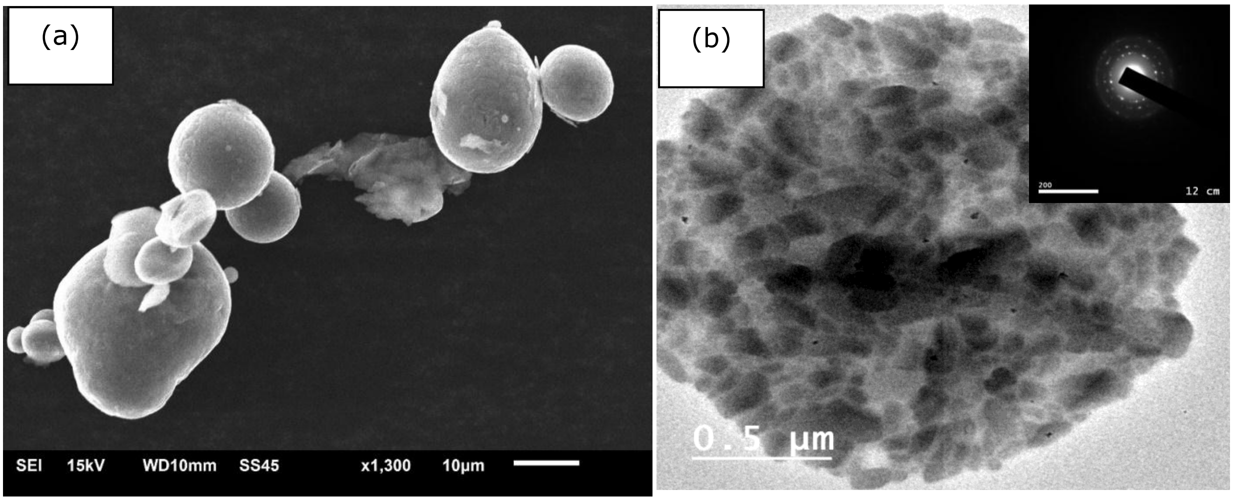

Figure 9. TEM micrograph of micron scale Al particles (a), nano-scale Al particles (b).

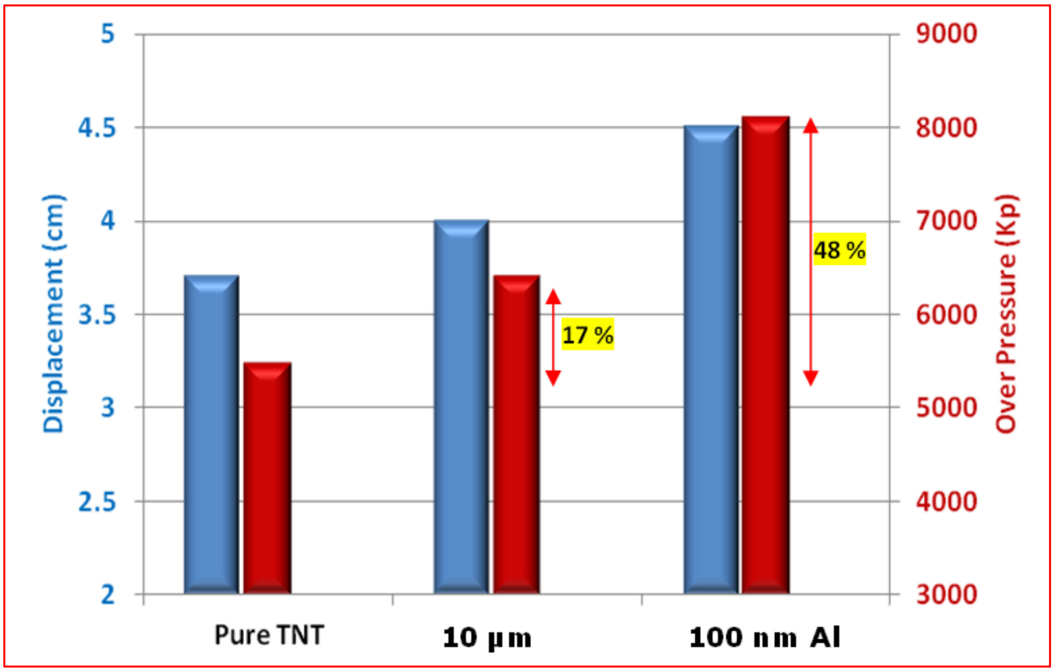

Figure 10. The impact of Al particle size on TNT workability

3.3 Destructive effect evaluation via Kast test

The impact of Al particle size on the destructive effect of TNT was evaluated using standard Kast test. The reduction of copper crusher height was precisely measured; the corresponding overpressure value was retrieved using standard charts. While, micron aluminium particles decreased the destructive effect of TNT by -6.5 %; Al NPs offered enhanced localized destructive effect of TNT by 21 % figure 11.

This novel finding could be ascribed to the fact that Al NPs could contribute more effectively within detonation wave front. Al NPs could offer enhanced heat output, combustion temperature, explosion force, and high detonation velocity. Consequently enhanced brisance can be achieved.

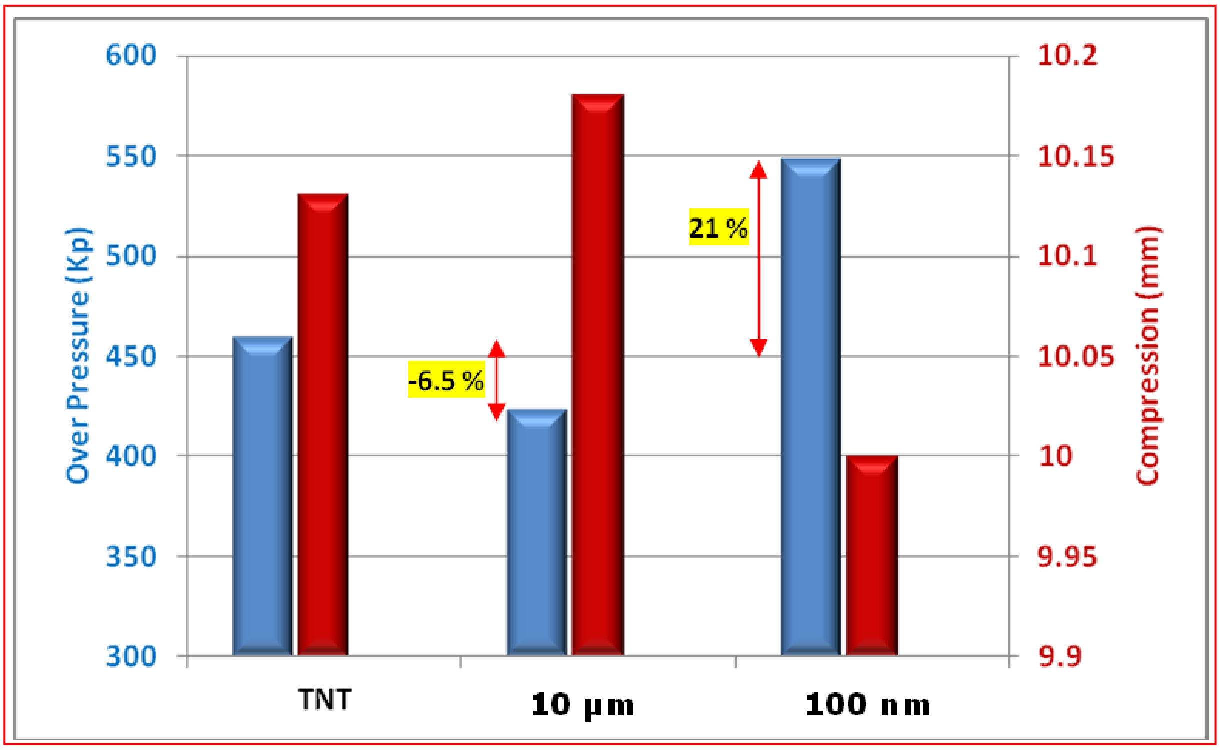

Figure 11. Impact of Al particle size on TNT brisance using Kast test.

3.4 Destructive effect evaluation via Hess test

The impact of micron and nano-scopic Al on destructive effect of TNT was further evaluated using Hess test. The compression in lead crusher height was employed as a measure of destructive effect relative to TNT. Explosive charge of 50 g was exploded; the height of lead crusher was precisely measured. Whereas micron Al particles decreased the destructive effect of TNT; nanoscopic Al particles offered an increase in TNT destructive effect figure 12.

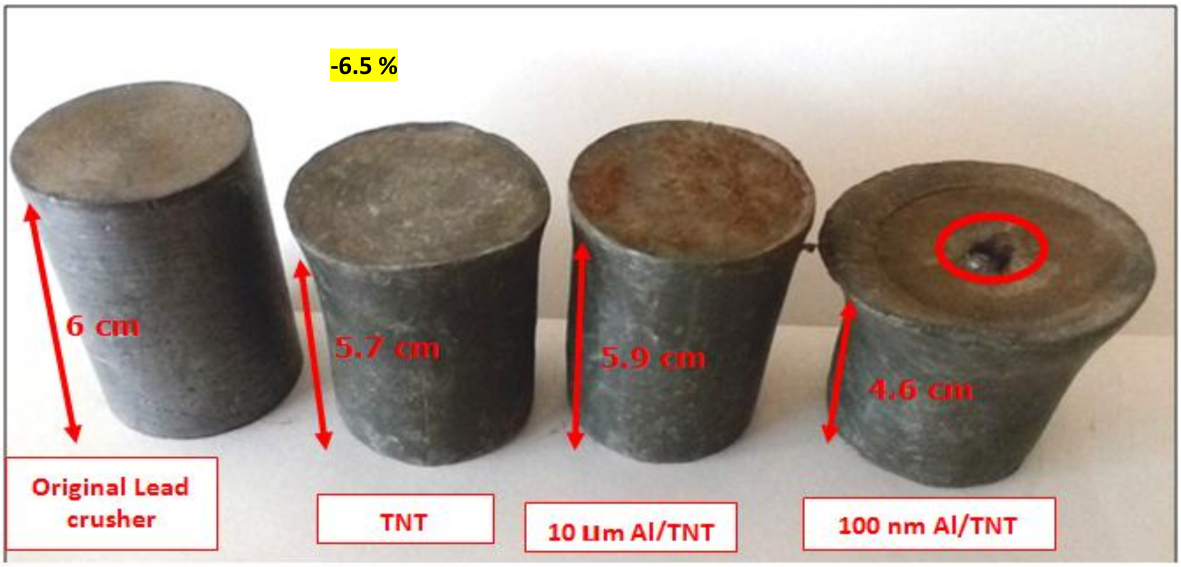

Figure 12. Effect of Al particle size on TNT brisance using Hess test

IOP Conf. Series: Materials Science and Engineering **975** (2020) 012009 doi:10.1088/1757-899X/975/1/012009

Whereas 10 µm Al particles demonstrated lead crusher height of 5.9 compared with 5.7 for TNT; Al NPs offered enhanced destructive effect as it offered lead crusher height of 4.6 cm compared with 5.7 cm of TNT. It can be concluded that micron-scale Al particles could contribute only to shock wave strength, with the expansion of gaseous products behind C. J. point. Micron-scale Al particles would act as inert material within detonation wave front prior to C.J. point.

These findings confirmed the findings by Kast test. It can be concluded that the effective integration of colloidal Al NPs could allow combustion to take place more efficiently within the detonation wave narrow zone. This zone lies in the order of few µm. This could withstand the enhanced destructive effect for Al NPs. The detonation action during Hess test was video recorded. Figure 13 demonstrates the moment of initiation (a), explosion of TNT (b), 10 µm Al/TNT (C), and 100 nm Al/TNT (d). It is apparently clear that Al NPs offered an enhanced fire ball action. This could withstand enhanced shock wave strength as well.

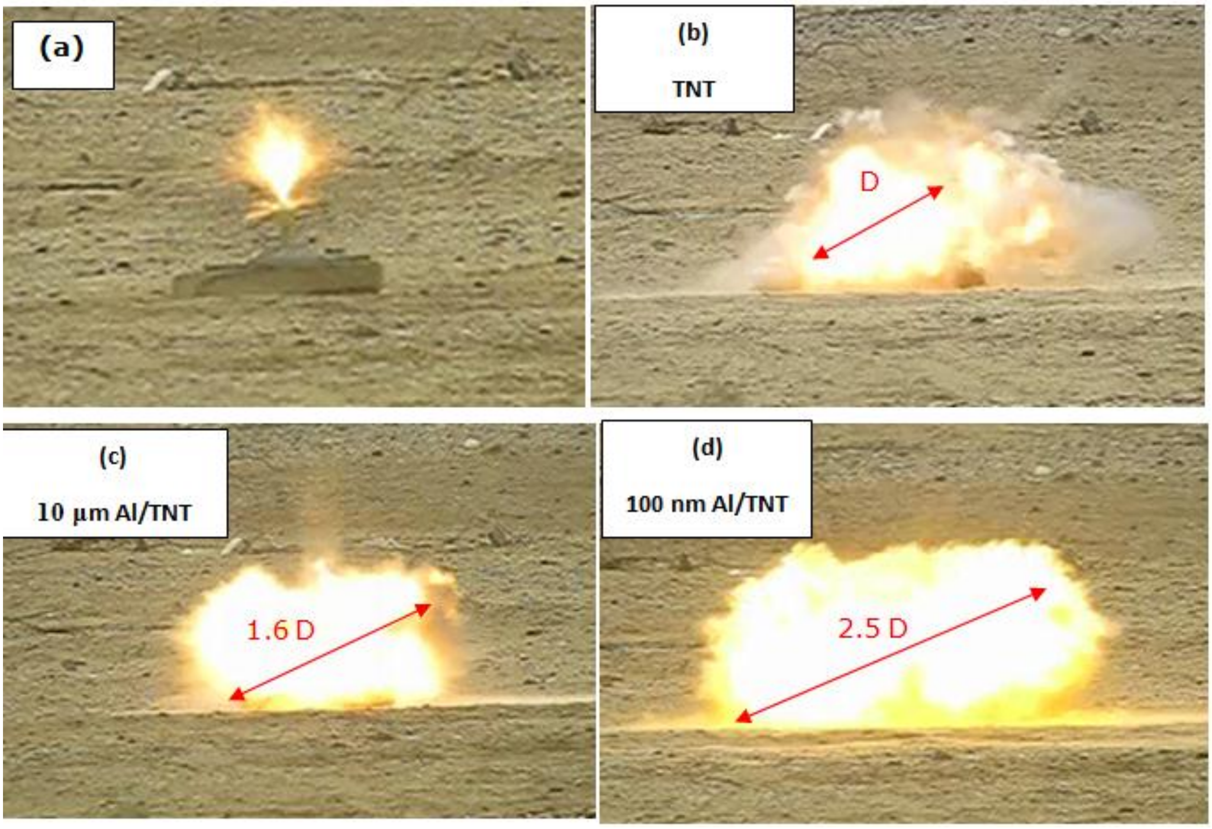

Figure 13. Hess test actions: moment of initiation (a), TNT (b), 10µm Al/TNT (C), 100 nm Al/TNT (d).

Al nanoparticles demonstrated extended fire ball with fireball diameter 2.5 times that of TNT, compared with 1.6 times for 10 µm Al/TNT. It is apparently clear that the Al nanoparticles not only contribute to the destructive effect within detonation wave front; but also excess fuel could contribute to the shock wave with efficient combustion. Therefore high thermal loading can be generated [1-2].

3.5 Detonation velocity measurement

Detonation velocity was determined by measuring the time required for the detonation wave to travel a measured distance longitudinally. Detonation velocity can provide information about detonation nature (ideal or non-ideal). 10 µm Al particles not only decreased the detonation velocity of TNT; but also it increased the critical diameter for detonation to take place. In contrast Al NPs offered ideal detonation reaction with detonation velocity higher than TNT. Furthermore Al NPs offered lower critical diameter figure 14.

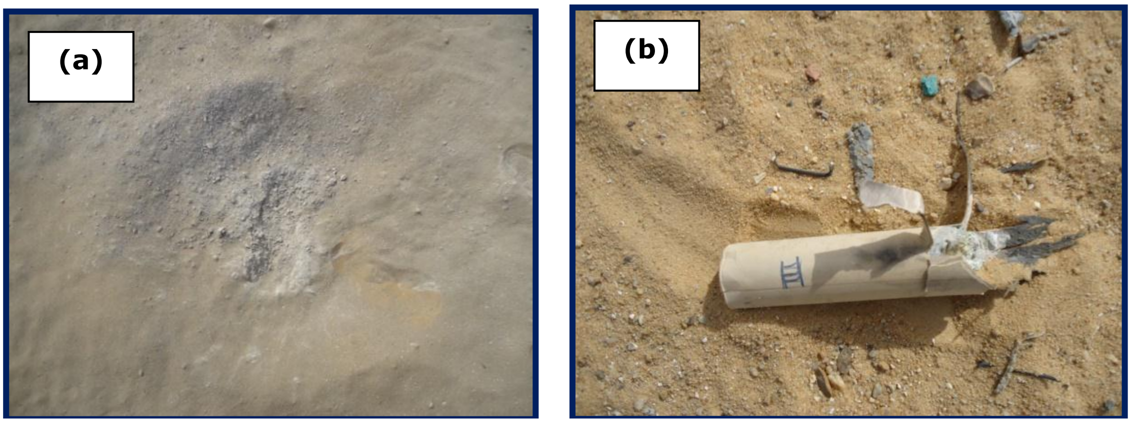

Figure 14. Ideal detonation for Al(100 nm)/TNT (a), no reaction for Al (10 µm) /TNT (b), at charge diameter of 40 mm.

It can be concluded that while commercial Al particles could act as a desensitizer, nanoscopic Al particles could act as a sensitizer. Therefore Al NPs could offer super-ideal detonation proceeding with superior detonation velocity [32-33]. Whereas TNT demonstrated detonation velocity of 5650 m/s; Al (100 nm) /TNT offered super-ideal detonation with detonation velocity of 6330 m/s.

4. Conclusion

This study shaded the light on Al NPs as a novel high energy density material that could offer not only enhanced shock wave strength but also brisance compared with conventional Al particles. It can be concluded that while conventional Al could contribute only to gaseous products behind C.J. point; Al NPs could contribute not only to shock wave strength but also with the detonation wave front with an increase in the brisance of explosive material. Al NPs offered lower critical diameter of TNT. Whereas Al NPs could act as a sensitizer at C.J. point; conventional Al particles could act as desensitizer. Enhanced dispersion characteristics could be achieved by integrating colloidal metal particles into TNT.

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