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The impact of various metals on the performance of TNT

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The impact of various metals on the performance of TNT

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Abstract: In blast applications, investigations involving energetic materials and various reactive metals are conducted. Some examples of such metals include copper, aluminum, and magnesium aluminum composite (magnalium). On the other hand, aluminum's cheap price, good dependability, and very high heat of combustion make it the most widely used gasoline additive. In this study, lab-scale formulations of metalized high explosives were made using TNT and various metallic fuels (Cu, Mg-Al, and Al). Then, using DSC and performance parameters measured by ballistic mortar, the researchers evaluated the explosives' workability and destructive effect, as well as the impact of the metal fuels on TNT's thermal behavior (Brisance by Kast). Results showed that the melting point of TNT shifted to lower temperatures due to the various metallic fuels (Cu, Al, Mg-Al). The Al with TNT sample also had the greatest brightness of the ones we looked at.

Keywords: Metalized explosives, Thermal behavior, Brisance, Workability.

1. Introduction

The formation enthalpies of mono-molecular energetic chemicals like TNT, RDX, and HMX set them apart from other compounds [1]. Research on other modern, extremely energetic explosives has shown promising results, including excellent explosive performance [3], thermal stability, and better activation energy-related metrics [2]. Metalized explosives have recently been the subject of many research programs due to their high densities and high combustion energy. The explosives business often employs the practice of incorporating reactive metal particles into explosives. An example of an additive is aluminized explosive, which is made from aluminum (Al) powder. Complete oxidation of aluminum releases over 30 MJ/kg of energy, while the usual explosive releases only 5-6 MJ/kg. Because of this, the energy density is significantly increased once aluminum is added.

Increasing the heat emitted with an elongation of the pressure pulse length is achieved by adding metal fuel powders to the energetic materials [4]. Since it is abundant and has many technical applications, reacts with oxygen in the air to form a protective oxide layer that makes it safe to handle and process, has a high thermal conductivity that increases combustion and, by extension, reactive power [5], and is relatively inexpensive, aluminum is the most used metal for doping particles.

Aluminized explosives have found several uses in recent decades, including Hexal, Tritonal, Ammonal, aluminized PBX, and many more. Typically, as gaseous detonation products expand after the detonation wave head, the Al particles in aluminized explosives react. Instead of reacting, the metal particles only exist in the reaction zone as an inert component [6]. Explosives and propellants often employ metals as fuel. Because of their high combustion heat and appropriate reaction kinetics, micron-sized aluminum powders are the most common.

Nevertheless, the total efficiency is reduced since the oxide coatings on the metal surface cannot serve as fuel. Adding aluminum to PBX formulations based on polyurethane as a binder has been reported in many papers, but at the cost of (HMX) octogen. In a comparison with the 84/16 HMX/PU formulation, this PBX resulted in a 5% decrease in detonation velocity, specific gas volume (V0), and brisance (B), but a considerable increase in explosive heat (Qv) and temperature (Tv). When the aluminum concentration reached 15%, the explosive force (F) reached its maximum. The explosive power (Qv x Vo) and brisance (F ρ D) were maximized when 25% Al was used. Figure (1) represents the results of Makhovin's investigation into potential metals for use in the manufacture of metalized explosives [7].

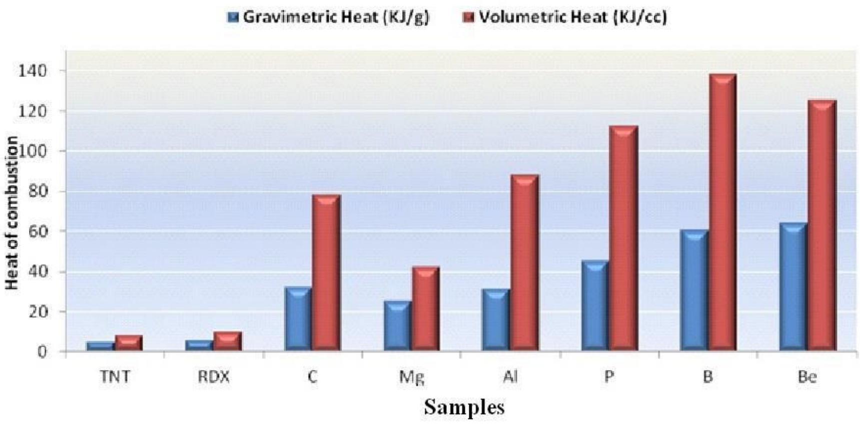

Figure 1. Energy density of common metallic fuels in comparison with explosives

When it comes to gravimetric and volumetric heat of combustion, boron is much superior than aluminum. In a calorimetric bomb test, boron fused to create more heat of explosion than aluminum coupled with HMX. At a flame temperature of 2067 ºC, Schaefer et al. [8] investigated the effects of boron, finding that incomplete burning occurred due to the formation of an oxide layer (B_2O_3) during surface layer burning, which reduced the likelihood of the oxidizer combining with the boron. The melting point of magnesium is 649 °C and its boiling point is 1107 °C; its combustion heat is 25.1 kJ/g. It is possible that magnesium, because to its high boiling point, is vaporized in the energetic composition and then burns with oxygen to boost the exothermicity of the process without absorbing any heat as an output [9]. An ideal metallic fuel would be inexpensive, resistant to air oxidation and moisture, and possessing high heat evolved properties. It would also be available in a range of particle sizes. Magnesium, an alloy of aluminum and magnesium, is a common material for this use. The melting temperature of magnalium, an alloy consisting of 50/50 magnesium and aluminum (Al_2Mg_3), is 460°C.

Magnalium outperforms all other individual component materials in terms of stability and exothermicity, and its reaction is slower when compared to magnesium, making it much more stable than pure aluminum [9]. Here are the thermal characteristics of popular metallic fuels, as seen in Table 1. In energetic formulations, copper's exceptional heat conductivity (400 w/(mK)) [10] is a result of the metal's ductility, softness, and malleability. A large quantity of gas is produced by reactive copper because, above 1000 ºC, CuO disintegrates, releasing free oxygen. A number of studies have shown the drawbacks of using certain metals in explosives, such as the toxicity of Beryllium and the high price of lithium [11]. Compared to other explosives, TNT has better sensitivity and stability, and it may be cast directly into warheads. It can also be mixed with high-energy explosives to create mixtures [12]. In this study, lab-scale formulations of metalized high explosives were made using TNT and various metallic fuels (Cu, Mg-Al, and Al). Then, using DSC and performance parameters measured by ballistic mortar, the researchers evaluated the explosives' workability and destructive effect, as well as the impact of the metal fuels on TNT's thermal behavior (Brisance by Kast).

Table 1. Metal fuels and their characteristics

Fuel	Melting Point (°C)	Boiling Point (°C)	Heat of Combustion (KJ/gm)	Products	Gm fuel/gm O
Al	660	2467	31	Al_2O_3	1.12
Mg	650	1107	25	MgO	1.52
Magnalium (95% Al + 5% Mg)	460	-	-	MgO/ Al_2O_3	1.32
Cu	1085	2560	1.25	CuO	0.25

2. Experimental

2.1. Chemicals
Particles averaging 6-8 μm in size, which are micron-sized copper. Particles of aluminum and magnalium, typically ranging in size from 7 to 10 micrometers.

2.2. Characterization of the metallic fuels
The morphology and dimensions of the metallic fuels (Cu, Mg-Al, Al) were analysed using a scanning electron microscope (SEM), specifically the ZEISS SEM EVO 10 MA, equipped with three different kinds of detectors. Secondary electrons (SE), backscattered electrons (BSE), and energy dispersive X-ray spectrometer (EDX) are features of the Bruker Quantax 200.

Table 2. Formulations based on TNT and metallic fuel with different ratio

No.	Formulation	Metallic fuel weight percentage (%)
1	Pure TNT	-
2	Comp. 1/ Al	12
3	Comp. 2/ Al-Mg	12
4	Comp. 3/ Cu	12

2.3. Integration of metallic fuels particles into energetic matrix
The developed formulations consisted of TNT and several metallic fuels, including Al, Al-Mg, and Cu. The quantities of TNT and other metals fuel were precisely measured. The TNT was melted at a temperature of 85°C using an ethylene glycol bath while applying strong suction to prevent contamination from vapors. Following the addition of metallic fuel, the melted TNT was stirred continuously for 40 minutes to ensure thorough mixing and homogeneity of the matrix. Ultimately, the liquid was poured into unique molds that are tailored to each individual test.

2.4. Thermal behavior of developed formulations with different metallic fuels
Differential scanning calorimetry (DSC) was used to quantify the impact of metallic fuels on the thermal characteristics of TNT. This analysis aimed to identify the temperature at which breakdown occurs and the amount of heat emitted during this process. The DSC Q-2000 instrument was used for this investigation. The sample was heated within a temperature range of 50°C to 350°C, with a heating rate of 5.0°C/min and a N_2 flow rate of 50 ml/min. The procedure for taking measurements may be further examined in reference [13].

2.5. Destructive effect evaluation using Kast method
The impact of various metallic fuels on the explosive power of TNT was determined by the Kast test conducted by PHYWE, a company based in Germany. A quantity of 2 grammes of the formulation was poured into an aluminum mold and the setup was built. Following the explosion of the charge, the steel cylinder (1), which was in motion, exerted pressure on the copper crusher (2), resulting in a change in the height of the crusher. The reduction in height is used to compute the overpressure in kilopascals (KPa). The technique for measuring may be further examined in reference [14].

2.6. Determine the workability by the ballistic mortar

The ballistic mortar test is used to assess the magnitude of shock waves produced by energetic materials. The ballistic mortar is a large steel mortar that is hung from a pendulum-like axis by a pendulum arm, as seen in Figure 2. The displacement of the mortar is quantified and contrasted with the displacement of other energetic substances. Here, 10 grammes of formulations containing various metallic fuels were used to determine the maximum displacement of the mortar. This displacement, measured using calibration charts, was then used to compute the maximum over pressure. This criterion is used to assess the workability of energetic formulations. The procedure for taking measurements may be further examined in reference [14].

3. Results and Discussion

3.1. Characterization of different metallic fuels

Scanning electron microscopy (SEM) has been used to examine the physical characteristics of the metallic fuels that were employed. Figure 3 displays representative SEM pictures of several fuel particles. The morphology of Cu Fuel particles exhibited spherical Cu particles with an average particle size of 6-8 microns (Fig. 3-a). Conversely, SEM micrographs of other fuel powders (Mg-Al & Al) displayed a small number of large particles with an overall average particle size of 7-10 microns. These particles formed dense agglomerates with smaller particles, which can be fully dispersed in the energetic matrix, as shown in Fig. 3-b and 3-c.

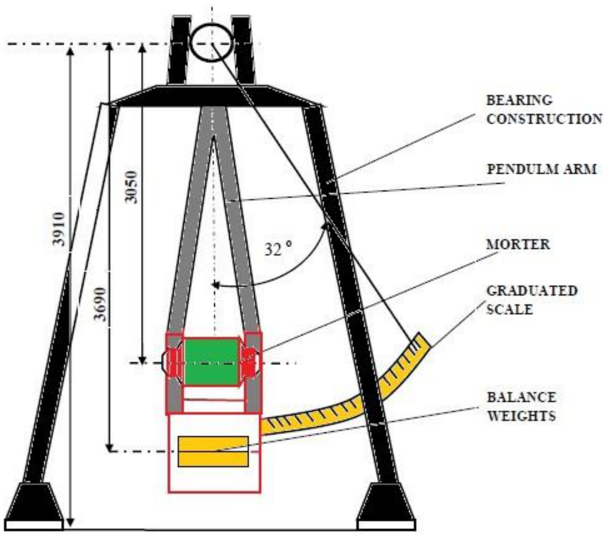

Figure 2. Schematic diagram of ballistic mortar

3.2 Thermal behavior of metalized formulations

Differential scanning calorimetry (DSC) is used to examine the response of a material to varying rates of heating. The thermal properties and differential scanning calorimetry (DSC) findings of TNT and metalized formulations are shown in Table 3. The thermograms of pure TNT and metalized TNT formulations may be seen in Figure 5. The DSC thermograms of pure TNT and metalized TNT formulations (12% wt. fuel) displayed an endothermic peak, indicating the melting of both TNT and metalized TNT formulations. However, the inclusion of various metallic fuels (Cu, Al, Mg-Al) caused a notable decrease in the melting point, as illustrated in table (3) and figure (5). This suggests the potential formation of eutectic mixtures and disruption in the crystal lattice. The impact of adding Al (with a high heat of combustion of 31 kJ/kg) in comparison to copper and magnalium is primarily defined by a significant exothermic deformation peak. This peak has a substantial influence on the overall heat generated after detonation, with a value of 759.7 J/g compared to 520.7 J/g for pure TNT. This may be attributed to the aluminum fuel's propensity to react with both oxygen and the inert reformulation gases, resulting in extra exothermic reactions.

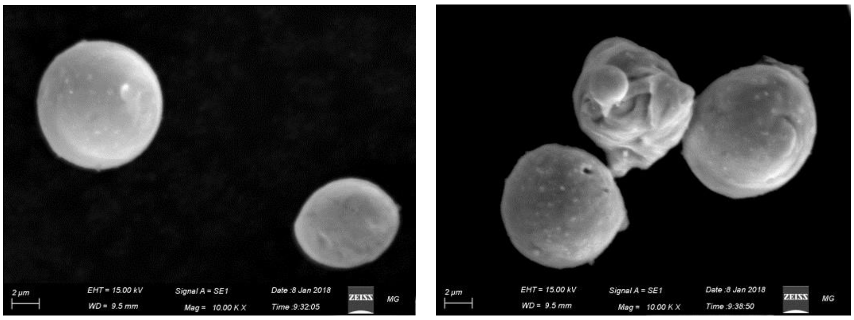

Figure 3(a). SEM of Cu particles

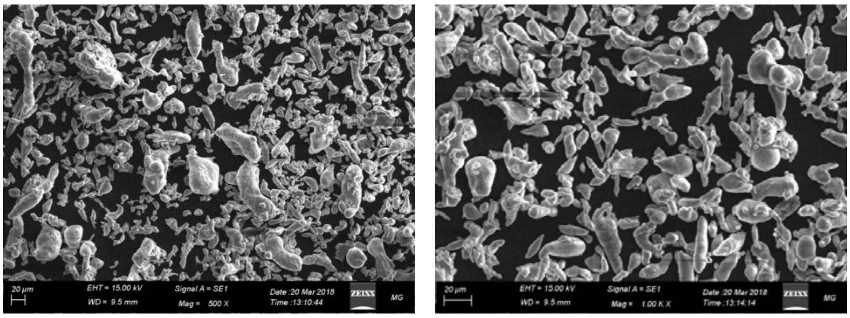

Figure 3(b). SEM of Al particles

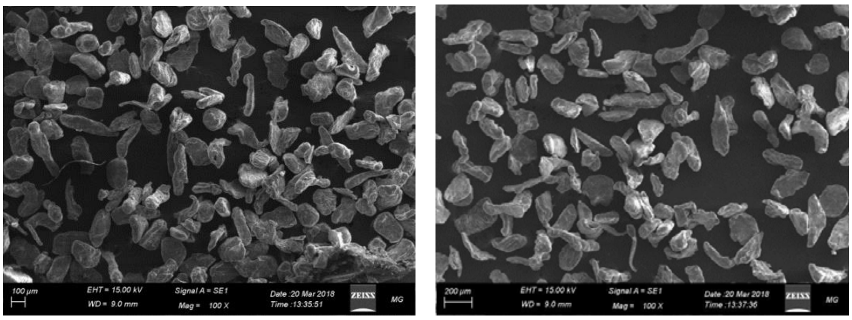

Figure 3(c). SEM micrographs of Mg-Al particles

Table 3. Thermal characteristics and DSC results of TNT and metalized formulations

Formulation	Total heat released (J/g)	DSC Results	
		Maximum Peak Temperature (ºC)	Melting Point (ºC)
TNT	520.7	292.02	80.74
TNT + 12 Cu	525.3	297.76	65.85
TNT + 12 Mg-Al	537	298.66	65.80
TNT + 12 Al	760	301.28	65.77

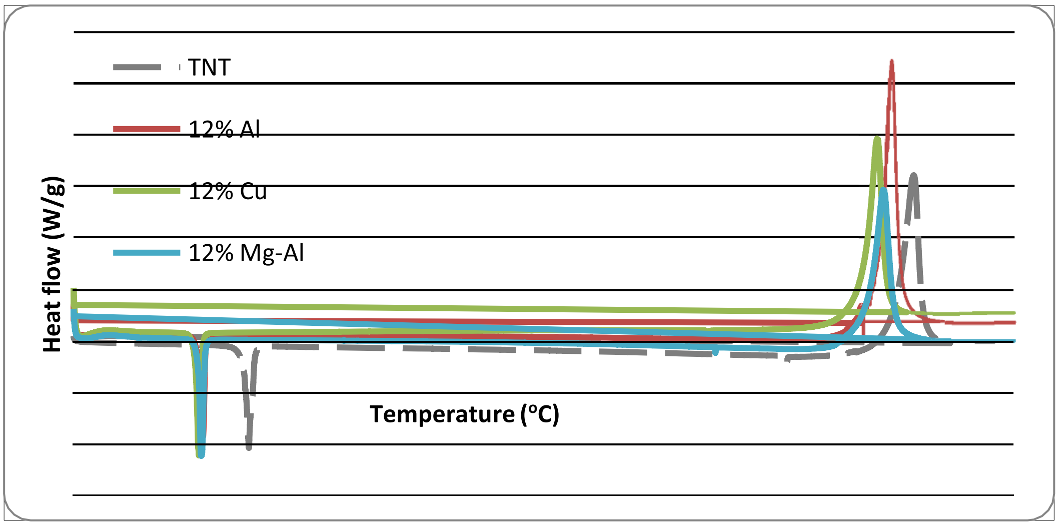

Figure 5. DSC of TNT and TNT based on Al, TNT based on Cu and TNT based on Mg-Al

3.3 Destructive effect evaluation using Kast method

The evaluated material's capacity for destruction is referred to as its brisance (B). The equation B = F ρ D represents the relationship between B, which is a reported value, and the variables ρ, F, and D. In this equation, ρ represents the density of the explosive, F represents the force of explosion, and D represents the velocity of detonation. The KAST approach was used to assess the effects of several metallic fuels (Cu, Mg-Al, Al) on the brisance of TNT. The reduction in the height of the copper crusher was converted into matching pressure values. Table 4 and Figure 6 demonstrate that formulations containing Mg-Al significantly increase the destructive effect by 60%. This is attributed to the high heat output of formulations containing magnesium, which leads to the initiation of detonation waves. The exothermic reactions of Mg-Al particles and their high temperatures contribute to achieving high explosion temperatures. Additionally, the strong affinity of Mg particles to evaporate with Al particles into the gas phase enhances the shattering effect.

Table 4. Explosive strength of the developed composites relative to TNT

Formulation	Copper crusher compression (mm)	Relative Compression (%)	Brisance in K_p	Relative Strength (%)
Pure TNT	10.13	100	459	100
12% Mg-Al	9.7	104.24	733	160
12% Cu	9.97	101.6	568	123.75
12% Al	10.28	98.5	356	77.5

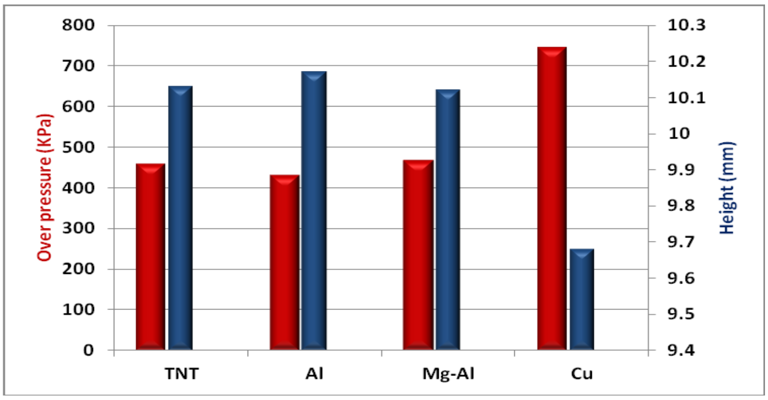

Figure 6. Effect of different metallic fuels on TNT Brisance

3.4 Workability evaluation using ballistic mortar

The findings from the ballistic mortar test are documented in table 5. The ballistic mortar's maximum displacement was clearly translated to equivalent quantities of overpressure. The addition of aluminum metallic fuel (12 wt%) resulted in a significant improvement in TNT workability, with an increase of 170%. The improved performance was attributed to the high heat produced by the combustion of aluminum particles (31 kJ/g), which results in strong mechanical work when exposed to accelerated detonation products. Additionally, the evaporation times of Mg-Al metal particles play a significant role in enhancing workability by 146%. This is due to the effect of magnesium, which lowers the ignition temperature of aluminum and bridges the gap between microsecond detonation reactions and millisecond burning reactions. Furthermore, the inclusion of Cu metal in the medium of the extremely exothermic detonation event has an additional purpose. At a temperature of 1000 oC, the CuO may be converted into gaseous oxygen, which significantly increases the total mechanical work of TNT by 125%.

Table 5. Explosive strength of developed formulations relative to TNT using Ballistic Mortar

Formulation	Displacement (cm)	Relative Displacement (%)	Workability in K_p	Relative Workability (%)
Pure TNT	3.4	100	4604	100
12% Cu	3.8	112	5776	125
12% Mg-Al	4.1	120	6724	146
12% Al I	4.3	126	7821	170

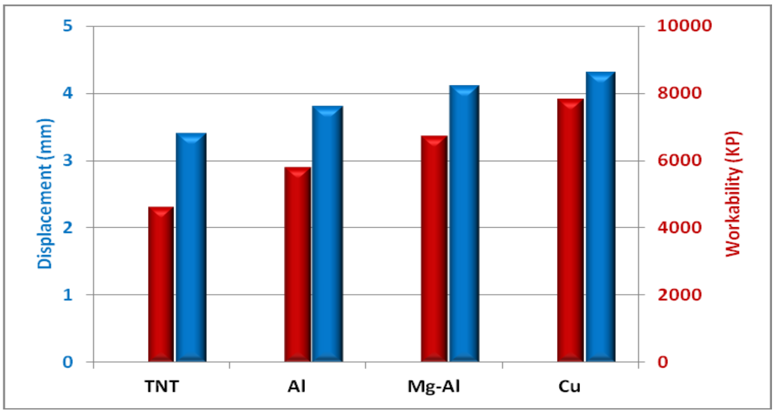

Figure 7. The workability results

4. Conclusion

Several reactive metals have been examined for their suitability when included into an explosive energetic matrix (TNT) in terms of their ease of use, capacity to cause fragmentation, and thermal characteristics. Experimental evidence has shown that the metalized TNT exhibits greater workability compared to pure TNT. Furthermore, upon examining the various samples, it was found that the sample containing aluminum combined with trinitrotoluene (TNT) had the greatest level of brisance. The inclusion of several metallic fuels (such as Cu, Al, Mg-Al) caused a notable decrease in the melting point of TNT. This indicates the potential production of eutectic mixtures and disruption in the crystal lattice. The research provides recommendations for many reactive metal components that might boost the performance of TNT, including as aluminum, magnesium-aluminum metastable alloy, and copper.

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