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Generation of ultrafine particles by high-velocity impact of metal projectiles on a metallic target

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ABSTRACT

In the present work, size distributions and total concentrations of ultrafine particles generated during high velocity impacts of metals are shown. The measure of ballistic-generated particles was performed under controlled impact conditions: Taylor cylinder impact tests were designed and performed using a light gas-gun facility. Two materials were investigated, high purity copper 99.99% and aluminum 7075 T6, with cylinders of two different lengths impacting against a steel anvil. Tests were performed in impact chamber and recorded with a high frame rate camera. High-resolution time measurements of particle distributions and total concentrations were performed through fast mobility particle sizer and aerodynamic particle sizer spectrometers as well as condensation particle counters. Particle emission factors in terms of number and mass were also evaluated.

The main result of the research was the measure of high particle generation in the ultrafine range: particle number distributions with a mode of 10 nm were detected; furthermore, number emission factors comparable to the ones typical of combustion phenomena were estimated. Finally, the number of particles emitted (larger than 10^{12} part impact^{-1} for both the materials) was found strictly related to the impact velocity and the contact surface area between projectile and anvil: these findings seem to indicate that the friction phenomena govern the particle formation process.

1. Introduction

Ultrafine particles (UFPs, particle diameter <100 nm) are produced by several indoor and outdoor sources; therefore, a number of studies aimed at characterizing particle emission sources were carried in the last years. They found that fine and UFPs mainly come from anthropogenic activities involving combustion phenomena such as industrial processes, traffic, and indoor sources (Buonanno et al., 2009a, 2010, 2011a; Cass et al., 2000; Morawska et al., 2008; See & Balasubramanian, 2011).

Unlike combustion generated particles, a lack of understanding of UFP generation through mechanical processes still remains. Even if fragmentation phenomena (i.e. particle formation due to a violent collision of bodies with a large relative velocity) due to the application of high-energy stress could lead to the formation of UFPs (Brilliantov et al., 2009), no experimental studies were performed to quantify them.

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In the frame of workplace environments, particle generation phenomena through mechanical processes can be also addressed to ballistic impacts. Indeed, from a health perspective, the understanding of UFP generation due to ballistic impacts is of great concern since the aerosol produced in such events is made up of toxic heavy metal particles such as lead, tungsten heavy alloys, depleted uranium (DU): as example, submicron uranium oxide particles are amongst the alleged reasons of Gulf War and Balkan syndromes (Busby, 2010). Therefore, it could be interesting to evaluate the exposure to UFPs of people implicated in battlefield scenarios: in fact, soldiers involved in the friendly-fire events were exposed to ballistic-generated aerosol particles by inhalation, oral, and dermal pathways (Committee on Toxicology, 2008).

In order to assess the particle exposure experienced by crewmembers and first responders in battlefield scenarios, several experimental analyses were carried out sampling aerosol particles generated through the impact of heavy metal penetrators against armored test vehicles (Gold et al., 2007; Parkhurst & Guilmette, 2009). For example, the US Army performed the Capstone DU Aerosol Study to provide information on the amount and characteristics of aerosol particles generated in, or near, vehicles hit by a large-caliber DU penetrator striking Abrams or Bradley test vehicles (Cheng et al., 2009; Holmes et al., 2009; Parkhurst et al., 2009; Parkhurst & Guilmette, 2009). Such studies reported measurements of mass particle concentration decay over time as well as mass particle distribution inside and outside tanks: total mass concentrations of thousands of mg m^{-3} inside the tanks were detected (Gold et al., 2007; Cheng et al., 2009; Holmes et al., 2009). In such experimental analyses particle mass measurements were performed through gravimetric technique: particles were sampled through cascade impactors or cyclone separators in the target vehicles as a function of elapsed time after the shot, therefore, particles mass concentrations and chemical composition were obtained. However, such methods only allowed obtaining results in terms of mass concentrations and distributions of particle larger than 400 nm; therefore, UFP size distributions and concentrations could not be detected. On the contrary, Machado et al., 2010 used a transmission electron microscope (TEM) to investigate particles produced through ballistic impacts involving tungsten alloy penetrators into steel target plates; they found UFPs down to about 5 nm in diameter showing that it is noteworthy to quantify the UFP production due to impact episodes.

Significant UFP generation via non-hot mechanical processes were also measured in workplace environments during grinding (Maynard & Zimmer, 2002; Zimmer & Maynard, 2002; Knieke et al., 2009), fettling (Elihn & Berg, 2009; Elihn et al., 2011) and milling processes (Mohamed, 2003, 2010; Kurlov & Gusev, 2011). The governing process leading to the UFP formation was expected to be the gas-to-particle conversion phenomena: the high energy involved in attrition-based processes leads to the metal vaporization and to the consequent rapid condensation of the metal vapors. The evaluation of the minimum achievable particle size, as well as the minimum required energy, is a complex function of structural and thermodynamic properties of the considered metal, as example, the final grain size scales are related to the melting point and the bulk modulus (Eckert et al., 1992; Kurlov & Gusev, 2011).

Summarizing, the scientific community has not yet produced studies aimed at quantifying the aerosol produced by ballistic impact in terms of particle number. To this purpose, an experimental campaign was designed to perform non-penetrating high velocity impacts of aluminum and copper projectiles on steel target. The experiments were carried through a light gas-gun able to accelerate the projectiles as far as a chamber where the impact occurs and particle measurements are performed. High-resolution time measurements of particle distributions and total concentrations were performed through particle sizer spectrometers and condensation particle counters. Particle emission factors in terms of number and mass were also evaluated by launching projectiles at different velocities in order to quantify the influence of projectile deformation rate on particle generation phenomena.

2. Experimental analysis

2.1. Taylor cylinder impact test: materials and methods

The Taylor cylinder impact test was initially proposed as a potential testing technique to determine the dynamic yield stress of a material (Taylor, 1948). The test involves impacting a right circular cylinder against a rigid target and making post-impact measurements of the deformed shape (Zukas, 1990). Since the basic assumptions underlying the theory proposed by Taylor are not met, the test is no longer used for the original purpose. However, since this method allows to obtain high strains, strain rates, and deformations in a relative simple way and in controlled conditions, it is largely used for constitutive and damage model performance verification and for material selection (Zukas et al., 1982).

In the present work Taylor cylinders were used to perform ballistic impacts in controlled conditions to measure size distribution and concentration of UFPs generated during high velocity impacts between metals. Two materials were analyzed: high purity copper 99.99% in the cold worked conditions (yield stress of 244 MPa) and aluminum 7075 T6. Taylor cylinders had a caliber of 7.6 mm and two different lengths: 23 and 38 mm whose masses were, respectively, 2.9 and 4.8 g for aluminum and 8.5 and 15.6 g for copper.

The impact tests were performed with the light gas-gun of the University of Cassino and Southern Lazio. The system consists of a reservoir containing the working fluid, a barrel in which the projectile is accelerated by the expanding fluid, and an impact chamber (2.5 m^3) where the impact occurs and the measurements are performed (Fig. 1). The reservoir is 600 mm long, with an outside diameter of 150 mm, for a capacity of 7.2 L. It can operate with both air and helium as working fluid at the maximum pressure of 200 bar. The barrel is 3500 mm long, with a caliber of 8.0 mm.