Journal of Physics: Conference Series **500** (2014) 182018 doi:10.1088/1742-6596/500/18/182018

Ultrafine particle generation by high-velocity impact of metal projectiles

L Stabile[1], G Iannitti[2], P Vigo[1,3], A Ruggiero[1,2], A Russi[1] and G Buonanno[1]

[1]University of Cassino and Southern Lazio, Cassino , I-03043 Italy
[2]Techdyn Engineering, Rome, I-00199 Italy
[3]PaLMer, Ferentino, Italy

E-mail: l.stabile@unicas.it; g.iannitti@unicas.it; vigo@unicas.it; a.ruggiero@unicas.it; aldo.russi@unicas.it; buonanno@unicas.it

Abstract. Ultrafine particle generation through mechanical processes was not carefully deepened so far, even if it could be related to the human health-based researches. In particular, the evaluation of ultrafine particles produced in battlefield scenarios can be useful to quantify the exposure of soldiers to particles carrying toxic heavy metals. In the present work ultrafine particle generation during high-velocity impact of metal projectiles was deepened performing symmetrical high velocity Taylor impacts of copper cylinder tests (Rod-on-Rod tests) by means of a gas-gun facility. Particle number distributions and total concentrations were measured through one-second-time resolution instruments in a chamber where impact events at different velocities were performed. Particle number generation per impact was also evaluated. Particle concentrations in the 10^6 part. cm^{-3} range were measured corresponding to particle generations higher than 10^{12} particles per impact, then comparable to those typical of combustion sources. Particle number distribution showed a unimodal distribution with a 10 nm mode. Summarizing, the performed experimental campaign revealed an extremely high generation of ultrafine particles from mechanical processes.

1. Introduction

The exposure to airborne particles was associated to several adverse health effects [1]. In particular, ultrafine particles (UFPs, particle diameter <100 nm) were recognized to cause harmful health consequences due to their ability in easily crossing the human respiratory system and depositing in the deepest regions of the lungs carrying toxic compounds [2-4].

UFPs mainly come from anthropogenic activities involving combustion phenomena such as industrial processes, traffic, and indoor sources [5-8]. Anyway, unlike combustion-generated particles, a lack of understanding in UFP generation through mechanical processes still remains. Even if fragmentation phenomena due to the application of high-energy stress could lead to the formation of UFPs [9], few experimental studies were performed to quantify it.

A possible area of interest in the evaluation of UFP formation through mechanical processes is the workplace environment and, in particular, the environments where ballistic impacts are usually performed, e.g. battlefield scenarios where soldiers are exposed to ballistic-generated aerosol particles. Aerosols produced during such events could strongly affect the human health since they are 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 [11].

Several experimental analyses were performed to evaluate the exposure to particles experienced by soldiers in battlefield scenarios by launching heavy metal penetrators against armored test vehicles [11-14]. Anyway, these were only focused on the measurement of super-micrometric particles, revealing total particle mass concentrations of thousands of mg m^{-3} in the surroundings of the impact area. Nonetheless, UFPs down to about 5 nm in diameter were recognized through transmission electron microscope (TEM) measurements of particles sampled during ballistic impacts involving tungsten alloy penetrators into steel target plates [15], however no measurements were performed to quantify the UFP production.

Studies aimed to measure the UFP generated via non-hot mechanical processes were only performed for activities typical of industrial workplace environments (e.g. welding [16]).

The present work wants to fill this gap evaluating the UFP generation during high-velocity impact of metal projectiles. Size number distribution, total concentration and emission factor of UFPs generated during Rod-on-Rod (RoR) impact tests of copper cylinders s(are discussed.

2. Experimental apparatus

2.1. Rod-on-Rod test: materials and methods

Ballistic experiments were performed launching a copper cylinder (high purity copper 99.98% in the cold worked conditions: yield stress of 244 MPa; length 48 mm, diameter 10.76 mm) against a steady cylinder with the same diameter hung with four nylon fishing lines for the alignment. RoR experiment was performed to avoid friction forces along the impact surface during impact, in order to integrate data already obtained with classic Taylor impact test against anvil [17,18].

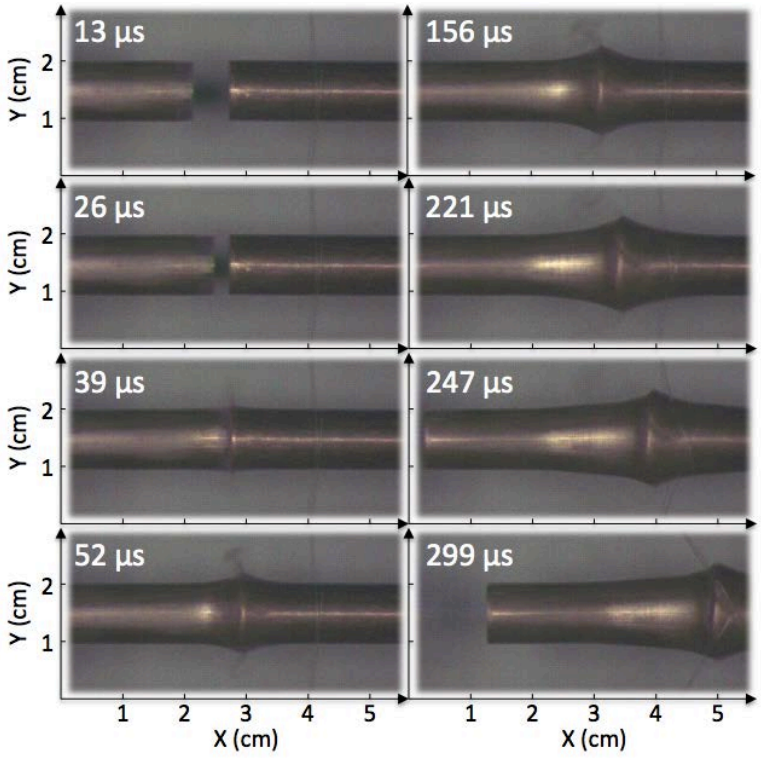

Figure 1. Photo sequence of RoR test (290 m s^{-1}).

Impact tests were performed with light gas-gun at the University of Cassino and Southern Lazio. The system consists of a reservoir containing the working fluid, i.e. air (7.2 L, maximum pressure 200 bar),

a barrel (3500 mm long) 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. The velocity of the impacting cylinder was measured by laser photodiodes. Each test was documented using high-speed video camera. In figure 1 a photo sequence of a RoR test performed at 290 m s^{-1} is reported.

In figure 2 the microstructure of copper specimens before impact and after impact is shown. In order to evaluate the effect of the plastic strain on the shape of the grains, the microstructure of the samples was measured *post mortem* very close to the impact surface. The average Cu grain size both before and after the impacts was about 20 μm, no significant microstructure changes were produced by the impact events themselves.

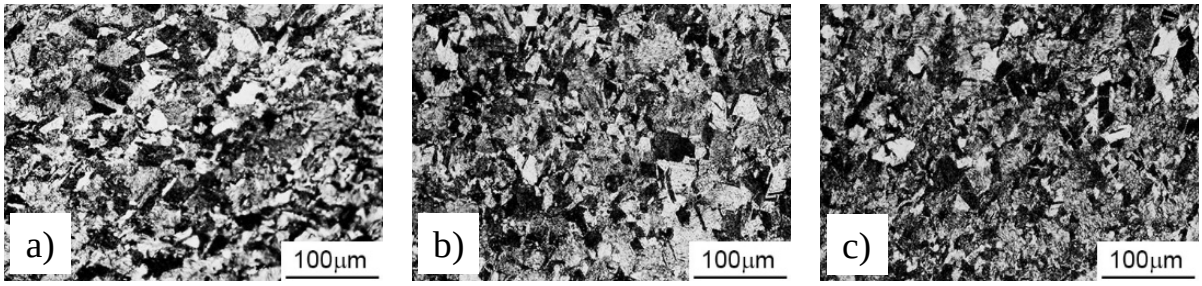

Figure 2. Microstructure pictures of copper specimens: a) before test; b) post-impact test at 230 m s^{-1}; c) post-impact test at 290 m s^{-1}.

2.2. Particle measurements

Since the impact of heavy metal projectiles could promote particle agglomeration phenomena rapidly changing particle sizes and concentrations, high-resolution time measurements of distributions and total concentrations were performed. In particular, particle number distributions and total concentrations were measured through 1-s time resolution instruments:

- Condensation Particle Counters (CPC 3775, TSI Inc.) able to detect airborne particles down to 4 nm in diameter and a maximum total concentration equal to 1×10^7 part. cm^{-3};
- Fast Mobility Particle Sizer spectrometer (FMPS 3091, TSI Inc.) able to measure sub-micrometer aerosol particle number distributions and concentrations in the range 5.6–560 nm. The instrument draws an aerosol sample into the inlet continuously. Particles are positively charged to a predictable level using a corona charger. The charged particles are then introduced to the measurement region near the centre of a high voltage electrode column and transported down the column via clean sheath air. A positive voltage is applied to the electrode that creates an electric field that repels the particles outward according to their electrical mobility. Charged particles strike the respective electrometers and transfer their charge. A particle with high electrical mobility strikes an electrometer near the top, whereas a particle with lower electrical mobility strikes an electrometer lower in the stack. The use of highly sensitive electrometers allows for concentration measurements of multiple particle sizes simultaneously.

CPC and FMPS sampling tubes were placed at about 50 cm from the impact area. Particle mass concentrations were not performed since a negligible particle mass amount was measured during similar tests involving high-velocity impacts of metal projectiles on a metallic target [18].

2.3. Experimental methodology

2.3.1. Particle concentration and distribution measurements

Impact tests at two different velocities, 230 and 290 m s^{-1}, were performed. Three measurements were performed for each test.

CPC and FMPS samplings were simultaneously performed introducing tubes inside the chamber (rear of the chamber, about 1.5 m from the target). Tests were performed in clean environmental chamber.

Particle concentrations and distributions measured through CPC and FMPS, respectively, were corrected for diffusion losses likely occurring onto the inner surface of the connecting tubes; these losses can be significant in the considered sampling line (the path experienced by the aerosol before entering the measurement devices is about 2 m).

Particle diffusion loss correction was applied on the basis of the method proposed by Gormley and Kennedy [19]. The size-based correction was applied considering the particle size distribution measured by the FMPS. Moreover, the dilution effect caused by the air volume expanding from reservoir to the impact chamber was evaluated as a function of the air pressure in the reservoir. In order to estimate such dilution, an isothermal expansion process was assumed.

2.3.2. Particle emission factor evaluation

In order to estimate the particle generation due to the ballistic impact, the particle number emission factor (*NEF*) was evaluated through the equation proposed for indoor particle sources by He et al. [20],

$$NEF = V \cdot \left[\frac{C_{in} - C_{in,0}}{\Delta t} + \left(AER + k \right)_{\text{avg}} \cdot C_{in,\text{avg}} - AER \cdot C_{in,0} \right], \quad (1)$$

where C_{in} and $C_{in,0}$ represent the peak and initial particle number concentrations in the chamber, respectively, $(AER + k)_{avg}$ is the average total removal rate (taking into account the deposition rate, k, and the air exchange ratio, AER), $C_{in,avg}$ is the average particle concentration in the chamber during the concentration decay, Δt is the time difference between the initial and peak concentration, and V is the efficient volume of the chamber. As hereinafter reported, the particle generation is instantaneous, and then the removal rate terms (the second and third addends of the *NEF*) can be properly neglected.

3. Results and discussions

In figure 3 CPC concentration trend resulted from one of the tests performed at 290 m s^{-1} is reported. The CPC trend shows that particle generation process is instantaneous since concentration ranges from initial levels ($C_{in,0}$, about 1×10^4 part. cm^{-3}) to the peaks (C_{in}) within a very short time interval (Δt). CPC trend clearly demonstrates that sub-micrometric particles are produced through mechanical phenomena. After the peak the concentrations decrease.

Average particle number concentration peaks at 230 and 290 m s^{-1} impact velocities were measured equal to 1.84×10^6 and 3.18×10^6 part. cm^{-3}, respectively.

In figure 4 particle number distribution evolution over time measured by FMPS spectrometer is reported for one of the 230 m s^{-1} impact velocity test.

Distributions corresponding to ballistic impacts are unimodal with a peak at around 10 nm then showing considerable emission of UFPs from the ballistic event: this is an interesting result since very few scientific papers detected UFP formation phenomena through non-hot mechanical processes (typically industrial processes [21,22]). After the impact, dilution phenomena prevail on coagulation and condensation processes since no shifts of the mode towards larger particles were detected for several minutes.

On the basis of the particle concentration data and equation (1), a number of emission factors were evaluated equal to 4.6×10^{12} and 7.9×10^{12} part. $impact^{-1}$ for 230 and 290 m s^{-1} impact velocity tests, respectively, then showing that the impact velocity affects the particle generation phenomena. The number of particles generated instantaneously is comparable to that emitted by cooking activity in one minute [8] and one order of magnitude higher than the maximum particle number emitted by 1-kilometer driving of an European diesel-fueled vehicle according to the current European regulation on tailpipe emission limits (6.0×10^{11} part. km^{-1} [23]).

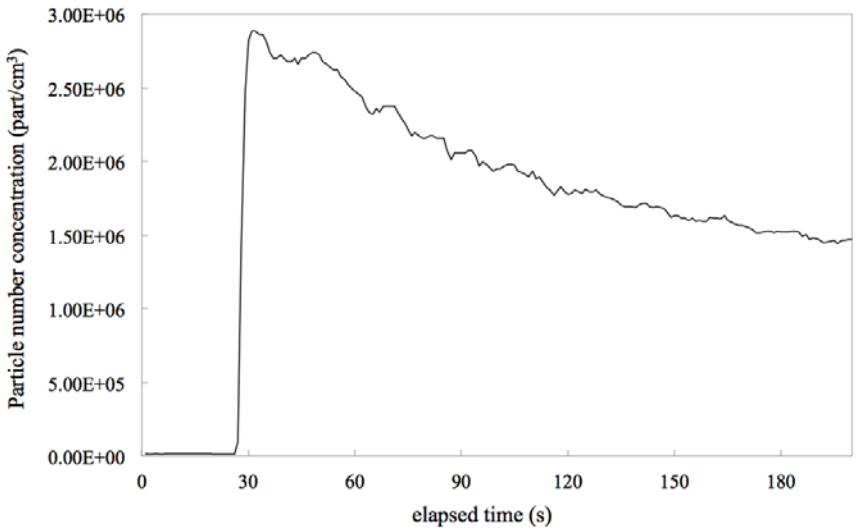

Figure 3. Particle number concentration measured for a test at 290 m s^{-1} through the CPC 3775

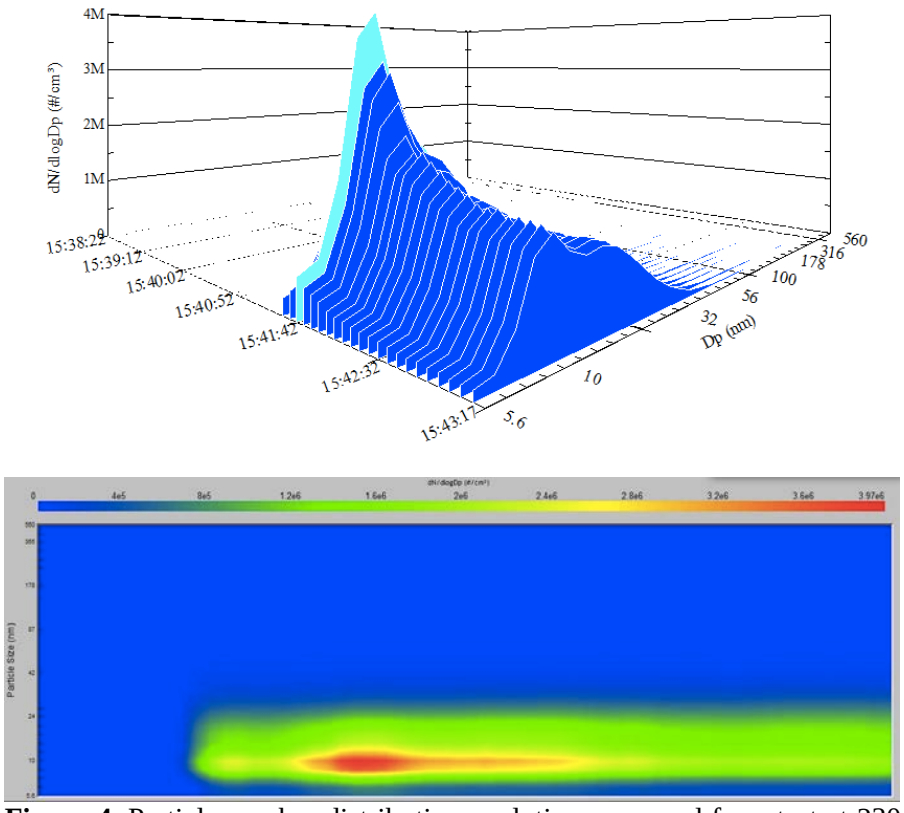

Figure 4. Particle number distribution evolution measured for a test at 230 m s^{-1} through the FMPS 3091.

4. Conclusions

The main result of the present study is the detection of a significant UFP generation by high-velocity impact of metals. In particular, the aerosol generated during RoR tests presents a particle distribution mode of 10 nm which is a mode typical of nucleation processes. In fact, a possible explanation for particle formation could be the metal vaporization process due to the high projectile surface temperature likely occurring during the impact even when no (or negligible) friction process is performed.

The number of particles emitted through the single RoR impact ($>10^{12}$ particles per impact) is comparable with (or larger than) the number emission factors of conventional sources involving combustion processes.

The authors point out that future development will be focused on particle formation mechanisms. Ad-hoc experiments will be performed to evaluate, through numerical simulations of the tests, governing parameters (stress-strain status, friction phenomenon, temperature) in particle formation phenomena.

References

[1] Miller K A et al. 2007 *New Engl. J. Med.* **356** 447
[2] Strak M et al. 2010 *Occup. Environ. Med*. **67** 118
[3] Schmid O et al. 2009 *Biomarkers* **14** 67
[4] Franck U, Odeh S, Wiedensohler A, Wehner B and Herbarth O 2011 *Sci. Total Environ.* **409** 4217
[5] Buonanno G, Fuoco F C and Stabile L 2011 *Atmos. Environ.* **45** 1434
[6] Buonanno G, Lall A A and Stabile L 2009 *Atmos. Environ.* **43** 1100
[7] Buonanno G, Stabile L, Avino P and Belluso E 2011 *Waste Manage.* **31** 2253
[8] Buonanno G, Johnson G, Morawska L and Stabile L 2011 *Aerosol. Sci. Tech.* **45** 1069
[9] Brilliantov N V, Bodrova A S and Krapivsky P L 2009 *J Stat Mech-Theory* E P06011
[10] Busby C 2010 Documents of the European Committee on Radiation Risk No. 2 Brussels
[11] Gold K, Cheng Y S and Holmes T D 2007 *Mil. Med.* **172** 393
[12] Cheng Y S, Kenoyer J L, Guilmette R A and Parkhurst M A 2009 *Health Phys.* **96** 266
[13] Parkhurst M A and Guilmette R A 2009 *Health Phys.*96 207
[14] Parkhurst M A, Cheng Y S, Kenoyer J L and Traub R J 2009 *Health Phys.* **96** 251
[15] Machado B I et al. 2010 *Int. J. Environ. Res. Publ. Health* **7** 3313
[16] Buonanno G, Morawska L and Stabile L 2011 *J. Aerosol Sci.* **42** 295
[17] Buonanno G, Stabile L, Ruggiero A, Iannitti G and Bonora N 2012 *AIP Conf. Proc.* **1426** 108
[18] Stabile L, Ruggiero A, Iannitti G and Buonanno G 2013 *J. Aerosol Sci.* **55** 66
[19] Gormley P G and Kennedy M 1949 *P. Roy. Irish. Acad.* A **52A** 163
[20] He C, Morawska L, Hitchins J and Gilbert D 2004 *Atmos. Environ.* **38** 3405
[21] Maynard A D and Zimmer A T 2002 *Ann. Occup. Hyg.* **46** 315
[22] Elihn K, Berg P and Lidén G 2011 *J. Aerosol Sci.* **42** 127
[23] Commission Regulation (EC) No 692/2008 of 18 July 2008