Mechanoluminescence of nylon under high velocity impact

2014 J. Phys.: Conf. Ser. 500 182005

(http://iopscience.iop.org/1742-6596/500/18/182005)

Journal of Physics: Conference Series **500** (2014) 182005 doi:10.1088/1742-6596/500/18/182005

Mechanoluminescence of nylon under high velocity impact

N Bonora[1,2], A Ruggiero[1,2], G Iannitti[2], C Abbate[1], F Iannuzzo[1] and G Busatto[1]
[1]University of Cassino and Southern Lazio, Cassino I-03043, Italy
[2]TECHDYN Engineering, Rome I-00199, Italy

nbonora@unicas.it

Abstract. The light emissions produced during deformation of solids induced by any mechanical action is called mechanoluminescence (ML). This phenomenon was reported mostly in hypervelocity impacts. Using high speed video-recording, the authors found evidence of ML for nylon at much lower impact velocity (of the order of 100 m/s). In order to understand the mechanism responsible for ML, Taylor impact experiments were planned and performed. Several impact configurations were investigated: Taylor anvil impact, Taylor impact on nylon anvil and rod-on-rod impact experiment. During the tests, the emitted light was measured using a wide-spectrum visible-to-infrared photodiode with response below 1 microsecond, and the signals were analyzed. The existence of a limiting impact velocity below which ML is no longer observed seems to be indicative of the fact that ML is controlled by the high pressure that is generated under uniaxial strain loading conditions. This result is consistent with the fact that, as soon as the compressive stress wave travels longitudinally in the Taylor sample and the pressure drops as a result of the arrival of the release waves, the ML no longer occurs. When tests were repeated in vacuum, no light emission in the visible range was observed. This finding seems to indicate that light emission occurs as a result of the oxidation of free radicals generated by the rupture of the polymer chains caused by the dynamic pressure wave.

1. Introduction

Materials may emit light under several circumstances. For what concerns solids, light emission can result from mechanical actions such as stress that causes fractures (fracto-luminescence), pressure that results in elastic deformation (elastic and piezo-luminescence), or rubbing (tribo-luminescence). In general, this phenomenon, resulting from any mechanical action on a solid, is indicated as mechanoluminescence. The phenomenon is not new. In 1605, Francis Bacon observed that lumps of sugar emitted light when rubbed [1].

Nearly 50% of all inorganic salts and organic molecular solids show fracto-luminescence while only a few exhibit elastico or piezo-luminescence. In the last decade, a range of materials have been obtained that emit an intense and repeatable light during their elastic deformation without fracturing. Recently, the possibility to use elastic-luminescent material as detector of impact was also proposed [2].

In shock compression physics, this phenomenon is known to occur at very high pressure. Light emission is observed in sapphire under shock loading from 40 to 60 GPa [3]. Impact-induced luminescence is also well known from hypervelocity impacts that are typical in interplanetary space. In laboratory experiments impact velocities are of the order of several km/s. Impacts are often performed with metal projectiles impinging on nonmetal targets, and energies are so high that vaporization occurs on impact [4].

In 2011, performing Taylor anvil impact tests on copper at ~200 m/s, the authors recorded intense light emission associated with the impact of the nylon sabot with the steel anvil. The phenomenon was captured using high speed camera at a frame rate of 40000 fps. Successively, the impact test was repeated launching only the sabot (without the carried Taylor cylinder) and again emission of light was observed. In figure 1 the sequence of selected frames of that video is shown. Here, the light generation is clearly visible although the video recording was performed with an external illumination of 20000 lumen. Starting from that observation, it was decided to investigate further the phenomenon in order to understand the mechanisms of the light emission under impact and its correlation with impact parameters (impact velocity, environmental conditions, sample size and mass, etc.).

Figure 1. Sequence of light emission in impact of nylon sabot at 200 m/s with 40 mm gun bore.

Figure 2. Example of nylon Tylor cylinder used to measure light emission under impact

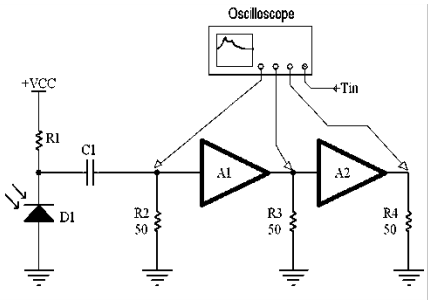


Figure 3. Scheme of the two stage amplifier circuit.

2. Material and experimental set-up

The material under investigation is commercial nylon 6.6 (Zellamid® 202) provided in form of extruded bar. It is a heavy duty, high impact, wear and heat resistant polyamide offering excellent machinability and chemical resistance. Impact tests were designed to quantify the emitted light under impact and to investigate the light emission under different conditions, such as impact in air or in vacuum, as well as a function of the impact velocity. Three type of impact tests were designed and performed:

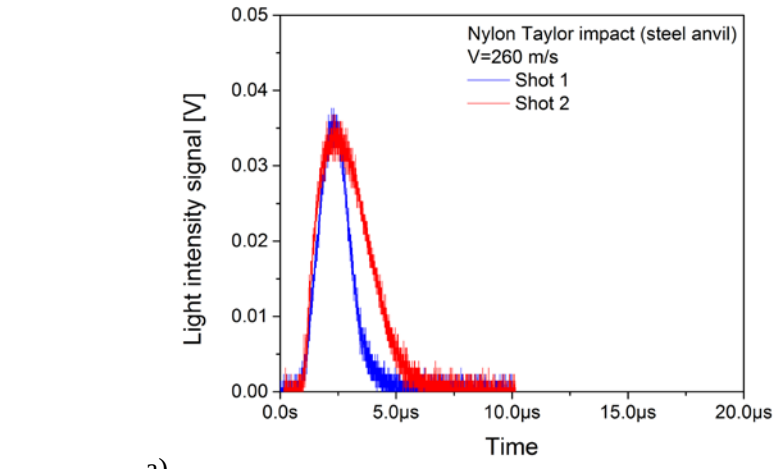
- Taylor anvil impact test (nylon cylinder against steel anvil);
- Taylor anvil impact against nylon anvil
- Rod on rod impact test.

Tests have been performed using cal. 12 (0.729″) and air as propelling gas. Nominal cylinder dimensions were 35.5 mm long and 18.1 mm in diameter (figure 2). In order to investigate the potential role of oxygen in the light generation process, tests have been repeated in vacuum using helium as propeller gas. Each test was video recorded using high speed camera (40000 fps, 4 μs exposure time).

Light emission during impact was measured by means of a two stage amplifier circuit (transresistance amplifier + linear amplifier) designed for the purpose, using a high speed PIN Photodiode (figure 3). The effect of the ambient light, on the measured emitted light, was taken into account. The sensor configuration can measure the light emitted in the 400-1100 nm wavelength range, which is wider than visible range, although it does not provide information about chromatic components.

Table 1. Two stage amplifier circuit parameters.

Parameter	Value
Input impedance	50W
First stage amplification	-100V/A (inv.)
Second stage amplification	100V/V (non inv.)
Amplification power	±10V



a)

b) 

Figure 4. a) Measured light emission intensity vs time for nylon on steel anvil impact at 260 m/s and b) sequence of high speed camera recording showing light emission at contact.

3. Results

Light emission was observed in all tests performed in air. The reference impact velocity for Taylor anvil (steel anvil) was 260 m/s, approximately. The Taylor impact on nylon anvil was scaled (increased velocity: 370 m/s) in order to have the same impact pressure in both tests. In the Taylor impact the duration of the light emission was approximately 4μs.

This time is smaller than the time interval between two high speed camera exposures. This imply that the camera not necessarily can record the event. Examples of the recorded emitted light signals are given in Fig. 4 - 6 for three impact experiments. In figure 4, Shot 1 and Shot 2 are at the same impact pressure as for Shot 4 in figure 6. Light emission was visually observed and recorded by the photodiode in all tests performed in air. In the case of the impact on nylon anvil, more emission of light was recorded. The measured light intensity peak value was the double of the peak measured in the impact against steel anvil. This seems to confirm the idea that the generation of light occurs as a result of the dynamic compression of nylon. *Post mortem* investigation did not reveal evidence of localized melting or burning, and this seems to support the conclusion that friction with the impact surface should not be responsible for the light emission. Furthermore, light emission was also recorded at lower impact velocity at which visually inspection did not reveal fractures or damage. To exclude the role of friction, rod-on-rod impact test was performed. In this type of test a nylon cylinder (impactor) is launched axially against another nylon cylinder (receiver) resulting in radial expansion without friction. Also in this test configuration, the emission of light was recorded.

Tests were repeated in vacuum, remarkably no light emission was recorded independently on the impact velocity or test configuration. This result is indicative of the key role of oxygen in the generation of light in the visible range.

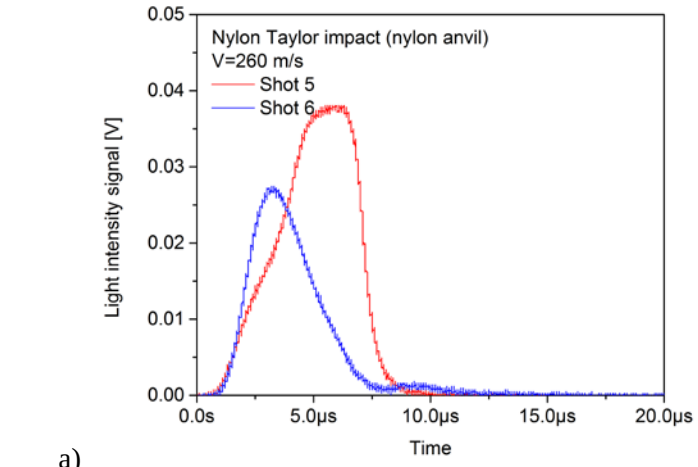


Figure 5. a) Measured light emission intensity vs time for nylon on nylon anvil impact at 260 m/s; b) sequence of high speed camera recording showing more light emission due to the anvil contribution.

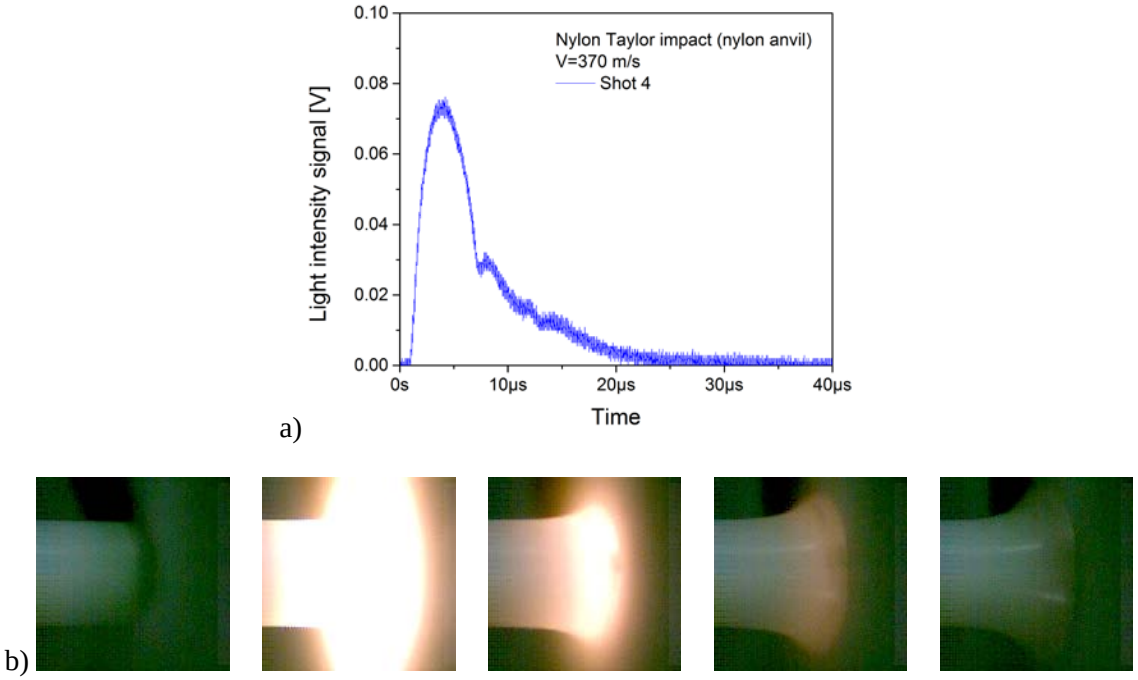


Figure 6. a) Measured light emission intensity vs time for nylon on nylon anvil impact at 370 m/s similar pressure of Shot1 and Shot 2; b) sequence of high speed camera recording showing light emission due to both Taylor cylinder and anvil.

4. Conclusions

In this work the light emission of nylon, under relatively low velocity impact (260 m/s and lower), was investigated. Several impact test configurations were investigated to identify the possible mechanism responsible for luminescence. The lack of macroscopic fracture or surface damage in samples impacted at low velocity seems to exclude fracto-luminescence as governing mechanism for light generation. Similarly, Taylor anvil impact on nylon anvil and ROR tests results seem to exclude tribo-luminescence. The fact that light emission is not measured in the tests performed in vacuum supports the conclusion that it occurs as a result of an oxidation process. It is known that the combined effect of heat and oxygen on polymers lead to a more or less intense light emission, usually indicated as chemiluminescence, resulting from the reactions of free radicals. In the case of polymer oxidation, free radicals, formed in a different initiating routes, ultimately leads to peroxyl radicals which provide potential light emitters in recombination reactions, [5]. In the case of dynamic impact, free radical are probably formed as a result of the shock compression and release process that triggers bond cleavage in the main polymer chain revealing a new form of mechano-chemiluminescence.

References

[1] Chandra B P 1998 *Luminescence of solids* Ed. Vij D R (Plenum, New York: Springer US) pp 361-389
[2] Chandra B P 2011 *J. lumin.* **131** 1203-10
[3] Zhang N-C, Liu F-S, Peng X-J, Wang J-G, Zhang M-J and Xue X-D 2012 *Acta Phys. Sin.* **61** 226501
[4] Klinkov K V and Rein M 2006 *J. App. Phys.* **100** 013529-1
[5] Matisovà-Rychlà L and Rychly J 2007 in *Developments in polymer research* Ed. Hopper H V (New York: Nova Science Publisher) 163-91