Forensic Science International 234 (2014) 95–102

Contents lists available at ScienceDirect

Forensic Science International

journal homepage: www.elsevier.com/locate/forsciint

The anatomy of a pipe bomb explosion: The effect of explosive filler, container material and ambient temperature on device fragmentation

Dana Bors, Josh Cummins, John Goodpaster *

Department of Chemistry and Chemical Biology, Forensic and Investigative Sciences Program, Indiana University Purdue University Indianapolis (IUPUI), Indianapolis, IN 46202, United States

ARTICLE INFO

Article history:
Received 5 August 2013
Received in revised form 7 October 2013
Accepted 8 October 2013
Available online 30 October 2013

Keywords:
Forensic Science
Explosives
Pipe bomb
Smokeless powder
Pyrodex
Fragmentation

ABSTRACT

Understanding the mechanical properties of different piping material under various conditions is important to predicting the behavior of pipe bombs. In this study, the effect of temperature on pipe bomb containers (i.e., PVC, black steel and galvanized steel) containing low explosive fillers (i.e., Pyrodex and double-base smokeless powder (DBSP)) was investigated. Measurements of fragment velocity and mass were compared for similar devices exploded in the spring (low/high temperature was 8 °C/21 °C) and winter (low/high temperature range was −9 °C/−3 °C). The explosions were captured using high speed filmography and fragment velocities were plotted as particle vector velocity maps (PVVM). The time that elapsed between the initiation of the winter devices containing double-base smokeless powder (DBSP) and the failure of their pipe containers ranged from 5.4 to 8.1 ms. The maximum fragment velocities for these devices ranged from 332 to 567 m/s. The steel devices ruptured and exploded more quickly than the PVC device. The steel devices also generated fragments with higher top speeds. Distributions of fragment masses were plotted as histograms and fragment weight distribution maps (FWDM). As expected, steel devices generated fewer, larger fragments than did the PVC devices. Comparison to devices exploded in the spring revealed several pieces of evidence for temperature effects on pipe bombs. For example, the mean fragment velocities for the winter devices were at or above those observed in the spring. The maximum fragment velocity was also higher for the winter steel devices. Although there were no significant differences in mean relative fragment mass, the fragment weight distribution maps (FWDMs) for two winter devices had anomalous slopes, where lower energy filler caused more severe fragmentation than higher energy filler.

Pipe bombs are composed of two basic components, the container and the filler. Containers are usually metal or plastic pipe, and fillers can have various energies and compositions. Once the filler is ignited and begins to deflagrate, the rapid increase of internal pressure ultimately causes the pipe to fail, thus generating an explosion. While deflagration is a well-known concept, a factor that has not been well-researched is the influence of environmental factors (i.e., temperature) on this process in actual pipe bombs.

Several studies have evaluated pipe materials (not pipe bombs) for their mechanical and tensile properties under varying conditions. Germain tested two plastics composed of poly-12-amino dodecanoic acid with high and low plasticizer content over a range of temperatures. He concluded that the hoop stress, defined as the circumferential stress required to increase the pipe diameter, is proportional to the plasticizer amount and inversely proportional to temperature [1]. It was also noted that the properties of these specific polymers are insensitive to the manufacturing process. In contrast, similar studies on PVC have shown that variability in manufacturing affects the behavior of the PVC. This raises the question of reproducibility between batch samples. Fluctuation of conditions during manufacturing can affect how the PVC responds to certain stimuli. Merah conducted tensile property tests on high density polyethylene (HDPE) and chlorinated polyvinylchloride (CPVC) pipes at temperatures ranging from −10 °C to 70 °C. He found that for both types of pipe, yield stress and the modulus of elasticity exhibited a linear decrease as temperature increased [2–4]. Numerical data depicting this trend in CPVC is shown in Table 1 [4]. This is expected since yield stress is the amount of stress required to stop the material from behaving elastically. Modulus of elasticity relates this stress to the resultant strain on the material. This value remains constant for a certain range of stress. However deviations from constancy will occur, which is called yield strength. Since yield strength is directly proportional to the modulus of elasticity, this property followed

* Corresponding author at: Forensic and Investigative Sciences Program, Indiana University Purdue University Indianapolis, 402 North Blackford Street LD326, Indianapolis, IN 46202, United States. Tel.: +1 317 274 6881.
E-mail addresses: jvgoodpa@iupui.edu, jvgoodpa@att.net (J. Goodpaster).

0379-0738/$ – see front matter © 2013 Elsevier Ireland Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.forsciint.2013.10.017

Table 1
Average values of CPVC mechanical properties obtained from weld specimens at different temperatures (Taken from Merah [4]).

Temperature (°C)	Number of tests	Yield strength	Elastic modulus	Fracture strain
−10	3	57	3360	2.3
0	3	53	3077	2.1
23	4	47	2823	2.4
50	3	37	2506	1.6
70	3	30	2322	1.7

the same pattern. Temperature appeared to have little effect on yield strain, or change in shape of the material, as it only slightly increased over the entire temperature range. One apparent difference in the two polymers was that at all temperatures, HDPE fractured in a ductile manner, meaning it showed substantial permanent deformation before breaking, whereas the CPVC exhibited ductile fracture above room temperature and brittle fracture, which exhibits little or no plastic deformation, below room temperature [2–4].

The effect of temperature on low explosives such as are found in pipe bombs has not been as extensively studied. McAbee and Chmura tested four double-base propellant formulations to observe the reactions of materials to forces applied under tension, known as tensile properties, over a temperature range of −60 °C to 80 °C. A general trend was that the duration of the explosion was pointedly longer as temperature increased. Also, the modulus and tensile strength were indirectly proportional to temperature. This means the resistance of the material to tearing increased as temperature decreased and vice versa. Irregularities were present however, leading to the overall conclusion stating, "...there is no simple way of predicting performance at one temperature from performance at another temperature" [5]. Hence, temperature-dependent changes in the pipe material itself may be more important in this case.

Overall, it is evident that effect of temperature on pipe bombs should not be ignored. The aim here is to focus on various pipe materials containing low explosives, where the behavior of similar devices at different temperatures is investigated.

1. Materials and methods

In general, the experimental setup was modeled after Bors et al. [6]. Devices were constructed from galvanized steel (Mueller Global brand), black steel (Mueller Global brand), or PVC, and were all purchased at Home Depot. The pipes were Schedule 40 with eight-inch pipe bodies and a one-inch nominal diameter. The metal pipes had scarf marks on the inside of the pipe body indicating that they were manufactured using an electric resistance weld. The two energetic fillers used were Hodgdon Pyrodex and Alliant Red Dot double-base smokeless powder (DBSP). All devices were capped at each end with one end cap having a 3/16 inch diameter hole for inserting igniter wires. The devices were assembled inside of a vehicle and then suspended approximately one foot off of the ground within an outdoor wooden containment structure.

On the date of the first spring event, the minimum temperature in Indianapolis, IN was 8 °C and the maximum temperature was 21 °C. The average dew point was 7 °C and the mean sea level pressure was 30.0 inHg [7]. In contrast, on the date of the second Winter event, the minimum and maximum temperatures were −9 °C and −3 °C respectively (with an estimated wind chill of −15 °C). On this day, the mean dew point was −9 °C and the average pressure was 29.8 inHg. Both events occurred in the morning, with an hourly temperature breakdown shown in Fig. 1. The amount of time that elapsed between the construction of the winter devices inside a vehicle at the test site and the initiation of the devices was not specifically monitored. However, after the set-up of the device, configuring the camera and clearing the area, devices were exposed to the outside air temperature for a minimum of 20 min. Calculations of the rate of conductive and convective heat loss from an 8-inch galvanized steel pipe under these environmental conditions yield an estimated equilibration time of under 10 min.

High speed video, using a frame rate of 30,000 frames per second, captured the explosions for the winter devices filled with DBSP. Photron FASTCAM (Photron, San Diego, CA) and ProAnalyst software (Xcitex, Cambridge, MA) were used to analyze the footage. Note that in the spring event, the camera was started at the same time as the activation of the electric igniter but only a set amount of frames before and after the start of the camera were saved. In the winter, the camera saved all frames beginning with the start of the camera, which coincided with the initiation of the device. Therefore, only the footage from the winter had a true "time zero" and it was analyzed to determine the time to explosion, which is the time elapsed between initiation of the device and the first breach of the container. The duration of the explosion, or the time elapsed between the first breach of the container to complete failure, was determined for all devices. Histograms and particle vector velocity maps (PVVM) were generated to show the distribution of fragment velocities for all devices.

Due to the inherent legal and safety issues in this experiment, all devices were assembled and deployed one at a time and only by personnel from the Indiana State Police Bomb Squad. Post blast fragments from each device were collected and placed into individual paint cans. Masses of the fragments were obtained using an analytical balance. The masses were plotted as histograms and FWDMs to depict the distribution in relation to pipe and energetic filler type. This paper will only focus on the behavior of six devices (three different pipe materials with two different fillers) and how they compare to the same type of device exploded in the spring.

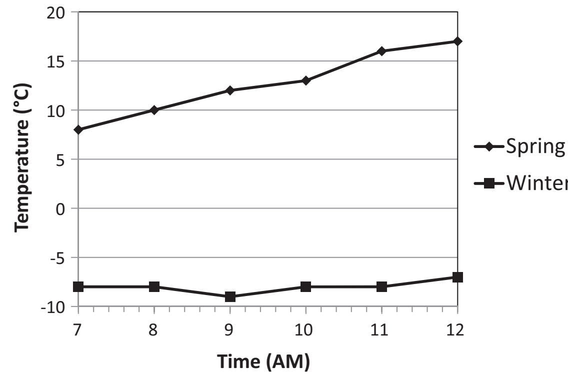

Fig. 1. Hourly temperature breakdown for both testing days. (http://weather.org/weatherorg_records_and_averages.htm).

2. Results and discussion

2.1. Effect of container material and filler type (winter devices)

High speed video was used to capture the explosions of three devices filled with DBSP. ProAnalyst software provided tracking of individual fragments and allowed for the calculation of fragment velocities. The distributions of fragment velocities for the three DBSP devices are depicted graphically using histograms (Fig. 2). The distribution of fragment velocities for the PVC device appears Gaussian in nature, compared to the more uniform distribution of the metal devices. Fig. 3 contains frames representing a stepwise sequence of the explosion of the PVC DBSP device. The second frame depicts the point of first failure of the pipe (located on the pipe body), hence the time to explosion for this device was 8.1 ms. Fig. 4 shows the trajectories of specific fragments mapped in a particle velocity vector map (PVVM), where the vast majority of the fragments are traveling at less than 305 m/s. An advantage of a PVVM is that it depicts fragment trajectory and fragment velocity, which are clearly not independent in this case. For example, there is a group of slower moving fragments clustered in the lower left corner, opposite the point of first failure on the pipe body.

Fig. 5 contains frames representing a stepwise sequence of the explosion from the black steel DBSP device. The second frame depicts the point of first failure of the pipe (located on the right end cap) with a time to explosion of 5.8 ms. The location of first failure is consistent with our prior observations of metal devices [6]. Note that the total time elapsed in Fig. 5 is only 170 μs. In Fig. 6, the PVVM for this device shows a broad range of fragment trajectories and velocities. Two fragments indicated in this plot were easily identified in the video and recovered post-blast. Given that their mass and velocity were known, it was possible to calculate