EXPLODING EXPERIMENT FOR QUALITY TEST OF WEAPON BARREL STEELS

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Abstract
The classical methodology for testing physical-mechanical properties of metallic materials usually requires laboratory conditions such as pulled-press equipments and usually takes a high costs. Sometime, these methods cannot be used to evaluate quality of weapon barrel steels under individual standards. This article presents an exploding experiment method for evaluation physical-mechanical characteristics of weapon barrel steels. The theoretical background of an explosion and effects of exploding wave on surface of an experimental metallic example is modelled and numerically simulated using 2D and 3D AUTODYN. The experimental procedure for evaluating quality of a metallic material example is implemented with high ability for practical application. This procedure has been used for testing quality of new metallic materials test-manufactured in the Department of Material Technology, Institute of Weapons as well as it is used for quality quick-test of weapon barrel steels made by metallurgical factories in Viet Nam.

Keywords:
Exploding experiment, barrel steels, metallic material testing, gun steels

1. INTRODUCTION
The weapon barrel is considered as an equipment which works in special conditions, very high gaseous product pressure (up to 250 MPa) and very high temperatures (up to 3500 °K), this phenomena occurs in a very short time period (up to $10^{-3}$ s ÷ $10^{-2}$ s). Gaseous product pressure reaches to a maximal value (peak point) at a point near to barrel bottom. The barrel of the 152 mm Self-propelled Howitzer ver.77, temperatures, and pressure in the barrel during firing cycle are depicted in Fig. 1 (on the left), see [3], [5].

![Fig. 1: The bore barrel and firing loads of the 152 mm Self-propelled Howitzer ver. 77 (rifles not depicted) (on the left), stress status in the barrel wall (on the right)](image-url)
The high propellant gaseous product pressure is loaded on inner surface of the barrel bore and induces a stress status in the barrel’s wall that is described in Fig. 1 (on the right), see [2], [4], [7].

If the maximum pressure developed in the combustion chamber or bore exceeds the elastic pressure of the gun barrel at any axial location, “permanent bore expansion” can result. In extreme cases, very high pressure can cause the barrel walls to rupture.

If the barrel material is brittle, the gun barrel can catastrophically “burst”. If the material is more ductile, “gas leakage” will occur, a far more preferable outcome than bursting.

Even at somewhat lower pressure, micro-cracks can form on the surfaces of the combustion chamber, forcing cone, and/or bore due to the firing environment. Over many hundreds or thousands of firing cycles, these can grow, coalesce, and eventually break through the barrel wall by a process known as “fatigue”.

Finally, unacceptable loss of material can occur on the forcing cone or bore that is caused either by the action of the hot gases passing over them at high velocity (a process called “erosion” which typically has thermal, chemical and/or mechanical bore degradation components) and/or by the projectile moving through the bore and interacting with the barrel walls (a process known as “wear”, which only has a mechanical bore degradation component).

In order to satisfy strength and service life of the barrel and to mitigate the above potential modes of failure, one of the important technology solutions is use of compatible quality steels for machining barrel. In general, modern gun barrels are manufactured from low alloy steel forgings. Steel has been found to be excellent material for this application due to its balanced combination of high elastic yield strength, surface hardness, ductility/fracture toughness, modulus of elasticity, end melting point. These properties enable the resulting gun barrel to be resistant to all of the potential failure modes described above. However, the desire for ever-increasing performance characteristics of weapon system in recent years has required that guns operate at higher pressure, as well as increased firing rates and durations. Further, the trend has been to utilize more energetic propellants that have higher flame temperatures and rates of bore degradation. Designers of gun barrel are under constant pressure to reduce weight, resulting in thinner walls, reduced thermal heat sink, and higher barrel operating temperatures. All of the above tend to increase the rates of wear and erosion inside the gun barrel, despite gun steel’s excellent combination of properties.

A very important procedure of gun barrel production technology is experimental procedure for gun barrel steels before machining. Due to the above-mentioned high-intensive operating environment of the barrel, the use of standard experimental methods for metallic materials quality test are not enough for evaluating gun steels. In order to simulate large most practical physical phenomena during firing cycle, it is necessary to apply an exploding experiment for evaluating gun steels.

In the following section we will study the typical responds to blast loads of a hollow steel tube.

2. THE SIMULATION OF RESPONDS TO EXPLODING LOADS OF HOLLOW STEEL TUBE USING AUTODYN

The non-linear analysis software AUTODYN-2D and 3D offer features and capabilities which allow us to model and simulate non-linear phenomena such as impact solids, explosion, interaction between solids as well as between solid and fluid flow (CFD). Importantly, the both include all the required function for model generation, analysis and display of results in a single graphical menu-driven package [1], [6].

AUTODYN offers some of solver for users to suite with different problem types. We will establish model of the hollow steel tube with an explosive core and simulate its responds caused by blast load using AUTODYN. In order to simulate this problem we will choose the 2D multiple materials Euler Solver that is characterized by a fixed Euler mesh, through which materials flow during exploding process. Thus, it is necessary to set up boundary conditions for the problem. In this case Flow-out procedure of Boundary condition function is used to set up flow-out boundary condition for the problem. Axial symmetry selection allows us to reduce quantity of elements and nodes of FEM model to suite for calculation in PC whose
processor speed is limited. The model is described in Fig. 2, including 3 gram of TNT explosive which is equivalent to a solid explosive cylinder with diameter of 14 mm, length of 12 mm; a hollow steel tube made of 1006 Steel, 4340 Steel or Steel 45 etc. with inner diameter of 14 mm, outer radius of 28 mm, length of 60 mm, air is defined as a component of Euler mesh but not depicted here; detonation point in red colour, gauge points 1, 2 and 3 are on equal distances of 5 mm.

![Fig. 2: The axial symmetrical model of the hollow steel tube and explosive core in AUTODYN, gauge points 1, 2, and 3, detonation point in red colour](image)

The result of simulation at time point of 4.38e-2 ms is presented in Fig. 3 (on the left). The material bulge occurs at the point explosive placed. The maximum diameter of the bulge depends on physical-mechanical properties of experimental material. The values of the young’s modulus, shear modulus, yield modulus, strength, and ductility/fracture toughness etc. of the experimental metal is higher, the value of maximum diameter of bulge is smaller, and oppositely, physical-mechanical characteristics of the example is smaller the value of the bulge is greater. By measuring the maximal diameter of the examples after blast at detonation point, length and quantity of fractures we can evaluate accurately quality of the examples. Material status of the steel tube at time point 4.38e-2 ms is shown in Fig. 3 (on the right). Radial deformation velocity and deformation value for Steel 45 at gauge points are shown in Fig. 4. It is clear that elastic and plastic status of metallic example occur simultaneously in material structure, especially intensively at point where the explosive core placed. The plastic deformation of steel tube can be used to evaluate quality of the metallic material. Physical-mechanical characteristics of Steel 1006 and Steel 4340 are shown in table 1.

**Table 1:** Some of physical-mechanical properties of Steel 1006 and Steel 4340

<table>
<thead>
<tr>
<th></th>
<th>Bulk modulus (kPa)</th>
<th>Reference density (g/cm³)</th>
<th>Specific heat (J/kg°K)</th>
<th>Shear modulus (kPa)</th>
<th>Yield stress (kPa)</th>
<th>Hardening constant (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel 1006</td>
<td>8.180e7</td>
<td>7.896</td>
<td>451.999</td>
<td>8.180e7</td>
<td>3.500e5</td>
<td>2.750e5</td>
</tr>
<tr>
<td>Steel 4340</td>
<td>1.590e8</td>
<td>7.830</td>
<td>476.999</td>
<td>8.180e7</td>
<td>7.920e5</td>
<td>5.100e5</td>
</tr>
</tbody>
</table>

![Fig. 3: The simulation result of the problem at 0.0438 ms, boundary conditions in orange colour (on the left)](image) The material status and bulge phenomena of the steel tube caused by exploding load (on the right)
Fig. 4: The radial deformation velocity (on the left) and radial deformation (on the right) of Steel 45 measured at gauge points 1, 2 and 3.

The simulation of the problem in AUTODYN is implemented for different gun steels that are made in Russian Federation, the simulation results are shown in table 2.

**Table 2:** The AUTODYN simulation results of different gun steels

<table>
<thead>
<tr>
<th>Point</th>
<th>Max. Bulge at gauge points (mm)</th>
<th>Min. Density of gauge point 1 (g/cm³)</th>
<th>Max. Pressure at detonation point (kPa)</th>
<th>Temperature at gauge point 1 (°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>1.45 1.12 0.87</td>
<td>7.62</td>
<td>4*10e6</td>
<td>393</td>
</tr>
<tr>
<td>35XΓCA</td>
<td>1.30 0.75 0.25</td>
<td>7.67</td>
<td>4*10e6</td>
<td>393</td>
</tr>
<tr>
<td>OXH1M-70</td>
<td>1.21 0.69 0.19</td>
<td>7.71</td>
<td>4*10e6</td>
<td>393</td>
</tr>
<tr>
<td>OXH1M-75</td>
<td>1.20 0.65 0.18</td>
<td>7.73</td>
<td>4*10e6</td>
<td>393</td>
</tr>
<tr>
<td>OXH2M</td>
<td>1.30 0.77 0.22</td>
<td>7.68</td>
<td>4*10e6</td>
<td>393</td>
</tr>
<tr>
<td>OXH3M-70</td>
<td>1.25 0.71 0.19</td>
<td>7.72</td>
<td>4*10e6</td>
<td>393</td>
</tr>
<tr>
<td>OXH3MΦA-80</td>
<td>1.23 0.70 0.17</td>
<td>7.72</td>
<td>4*10e6</td>
<td>393</td>
</tr>
</tbody>
</table>

3. **THE EXPERIMENT FOR EVALUATING QUALITY OF WEAPON BARREL STEELS**

The examples for exploding experiment are cut from the bottom of the barrel forgings. Schema for cutting examples and dimensions of an example are shown in Fig. 8 (on the left).

Fig. 5: The schema for cutting examples (on the left), dimensions of an example (in the middle), and the exploding experimental schema for evaluating weapon barrel steels (on the right).
The arrangement for exploding experiment is depicted in Fig. 5 (on the right), where there are following details: 1 and 6: PVC inserts, 2 and 5: fixed bases, 3: safety chamber, 4: steel example, 7: burning detonator, 8: ignition device. The solid explosive cylinder is placed into the hollow steel tube at the middle point along its symmetrical axis and it is fixed against moving or rotating in the inner of hollow steel tube. The explosive core is detonated by the burning detonator combined with an electrical primer.

The exploding experiment for evaluation of weapon barrel steels is implemented for 4 types of steels that are usually used in manufacturing gun barrels. The experiment results are compatible with calculation and simulation results, so the simulation model is suitable for studying exploding phenomena of an explosive core in a hollow steel tube. The bulges at three of gauge points are measured and presented in Table 3. By analyzing bulges, length of fractures and by observing shape of fractures, we can divide quality of gun steels into 5 quality levels as follows.

- **Quality level 1**: Bulge only occurs at detonating point. Fractures cannot be observed clearly (micro-cracks).
- **Quality level 2**: Fractures and bulge only occurs at detonating point. Fractures can be observed clearly, the length of each fracture is not greater than 15 mm.
- **Quality level 3**: Fractures and bulge only occurs at detonating point. Fractures can be observed clearly, their length may be greater than 15 mm but smaller than 30 mm.
- **Quality level 4**: Fractures can be observed most clearly, their length is greater than 30 mm and may pass through the length of examples.
- **Quality level 5**: Example is fragmented.

By comparing bulge of the examples after exploding experiment with simulation results and the above quality levels, we can evaluate quality of gun steels as shown in table 3. Imagines of some examples after exploding experiment and their respective quality levels are shown in Fig. 6.

**Table 3**: The radial bulge of some steel examples after exploding experiments

<table>
<thead>
<tr>
<th>Quantity of experiment examples</th>
<th>Maximum bulge measured at Gauge point 1 (mm)</th>
<th>Maximum bulge measured at Gauge point 2 (mm)</th>
<th>Maximum bulge measured at Gauge point 3 (mm)</th>
<th>Quantity of steel examples in each specific quality level</th>
<th>Place of productions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Level 1</td>
<td>Level 2</td>
</tr>
<tr>
<td>45</td>
<td>5</td>
<td>1.65</td>
<td>1.2</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>35Г1СА</td>
<td>14</td>
<td>1.50</td>
<td>0.82</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>ОХ3МФА</td>
<td>10</td>
<td>1.32</td>
<td>0.81</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>TSZ45-55</td>
<td>16</td>
<td>1.50</td>
<td>0.88</td>
<td>15</td>
<td>1</td>
</tr>
</tbody>
</table>

**Place of productions**

<table>
<thead>
<tr>
<th><strong>Place of productions</strong></th>
<th><strong>Quantity of steel examples in each specific quality level</strong></th>
<th><strong>Place of productions</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Russian Federation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viet Nam</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 6**: The exploding experimental results for weapon barrel steels
According to experiment results, the 35XlCA steel is quite brittle, and its strength is not as high as others gun steels, an experiment example of this steel is fragmented as shown in Fig. 6. The 35XlCA steel has been used to manufacture barrels of some recoilless weapons such as B40, and B41 shoulder-launched anti-tank weapons etc. Practically, it is observed that, despite of quite low gaseous product pressure (30 to 50 MPa) many gun barrels made from 35XlCA steel were bulged or fractured after hundreds of firing cycles. Weapon barrel steels are necessarily tested by the exploding experiment before applying for barrel manufacturing. Three examples are cut from each of barrel forging at the bottom and they are machined to have dimensions as shown in Fig. 5 (on the left and in the middle). The examples after exploding experiment need to satisfy quality requirements of quality level 1 to 3. If there is one example does not satisfy requirements of quality level 1 to 3, the barrel forging is eliminated.

4. CONCLUSIONS

The simulation results in AUTODYN-2D and 3D of the hollow steel tube loaded by blast pressure are variety such as material fracture, pressure, material damage, material crack, sound speed, material status (elastic, plastic, hydro) etc. The material bulge of the metallic tube measured at the detonation point depends on quality of the tube’s material and is used to evaluate quality of the metallic material. One of the advantages of the blast experiment method for evaluation of steel quality is lower-cost as well as it can be used as a quick-test in industrial production of metallic materials. It is especially suitable for quality evaluation of steels which are used for production of gun barrels due to ability to simulate real conditions occur into gun barrel in a firing cycle.

The future work is to simulate the exploding phenomena of explosive core in the hollow steel tube for more different types of gun barrel steels, to implement experiments and to measure parameters for establishing quality test standards for weapon barrel steels.

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REFERENCES