Effect of microstructure characterization on penetration performance and penetration mechanism of Fe-Al-Bi alloy shaped charge liner

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Abstract. Nowadays, an increasing number of new materials are used in shaped charge liner (SCL). However, most current work is focused on the density and high acoustic velocity of the SCL raw materials in order to improve the penetration depth of the SCL. This paper is going to introduce a Fe-Al-Bi alloy used for the SCL starting from new consideration of by importing the concept of 9 pressed sintering. The alloy’s matrix is Al. Core-shell structure particles which have ductile and tough Fe cores and hard Fe₃Al shells evenly distribute on the matrix. This paper analyzes the SCL’s continuous high-energy jet which is the core-shell structure particles covered by plasma state Al. The interaction between the jet and targets improve SCL’s penetration diameter and depth. It has been improved, compared with traditional SCL, the Fe-Al-Bi alloy SCL has better penetration performance.

1. Introduction

The shaped charge liner (SCL) is widely used in modern ammunition and certain industries, e.g. oil exploitation, mining, geology, etc. And SCL is one of the key units in shaped charge warhead[1-3]. After the detonation of warhead, the SCL materials are accelerated and collapsed along the axis of symmetry by high pressure of the detonating high explosive charge. In the process of collapsing, the jet is squeezed out with possible tip velocities of 9000-12000m/s to penetrate the target[4]. In most instances, greater penetration depth (P) into target depends on increasing jet density and increasing jet velocity. Pack and Evans proposed an equation $P = \left(\frac{\sigma_j}{\sigma_t}\right)^{1/2}L(1-\alpha Y/\sigma_j V^2)$ to describe the relation between penetration depth and the affecting factors, where $\sigma_j$ and $\sigma_t$ are the densities of the jet and the target respectively, L is the length of the jet which is largely decided by jet tip velocity, $\alpha$ is the empirical constant, Y is the target strength, and V is the jet velocity[5-6]. And there are many intricate equations proposed to predict the penetration depth of SLC. It can be observed that the factors influencing the penetrating ability of the jets are mainly considered to be density, velocity and effective length of the jet[7-9]. Therefore in order to obtain long continuous jet researchers prefer to choose SCL materials with high density and high acoustic velocity. However, the penetration process that jet acts on target is an extremely complicated process, which relates to material deformation under high pressure, high strain rate and high temperature. Simply taking density, velocity and length of jet into consideration to analyze the performance of SCL is incomplete. The penetration capability also depends on interaction mechanism between jet and target[10], and we should regard it as an important...
factor. But the research on the interaction mechanism between jet and target is still deficient. In addition to this, the penetration performance is not only penetration depth but also penetration diameter. In some instances, penetration diameter is even more important than penetration depth. But little research focus on penetration diameter, too.

In the present work, the SCLs made by series of Fe-Al-Bi alloys were selected to penetrate concrete targets. After the penetration test, the penetration depths and penetration diameters of the SCLs were compared. We discovered that the penetration performance of SCL is not only affected by jet density and jet velocity, but also evidently influenced by the interaction between the jet and the target. The microscopic features of the SCLs were examined and compared.

2. Experiments

2.1. Preparation of the SCLs

27Fe-63Al-10Bi (wt.%, Fe-Al-Bi), 36Fe-54Al-10Bi (wt.%, Fe-Al-Bi), 45Fe-45Al-10Bi (wt.%, Fe-Al-Bi), 54Fe-36Al-10Bi (wt.%, Fe-Al-Bi), 63Fe-27Al-10Bi (wt.%, Fe-Al-Bi) alloys were prepared by powder metallurgy. Fe powder (99.9% purity, particle size < 30μm), Al powder (99.9% purity, particle size < 5μm) and Bi powder (99.5% purity, particle size < 30μm) were used as original powders. The container was loaded with a blend of stainless steel grinding balls (balls size: φ10mm, φ5mm and φ1mm). The ratio of ball to powders was 10:1. Firstly, the mixture of Fe, Al powders were proceed with a planetary ball mill at 200 r/min for 20 h. And then Bi powders were added into the mixed powders and milled together for another 2 h.

With powder metallurgy approach, the Al-Fe-Bi composite powders were pressed to the pressing die by uniaxial pressing. Then the die was sintered at 620 °C for 2 h in the argon atmosphere.

2.2. Density of the liner

The equation \( \rho = \frac{W_1 \rho_0}{(W_3 - W_2)} \) is used to calculate the liners’ density, in which \( \rho \) is the density of the liner, \( W_1 \) is the weight of the liner in air, \( W_2 \) is the stable weight of the liner in water and \( W_3 \) is the weight of the liner in air whose open pores are full of water. And \( \rho_0 \) is the density of the water. The equation \( P = \frac{(V_0 - V)}{V_0} \times 100\% \) is used to calculate the poriness. \( V_0 \) is the apparent volume of the liner and \( V \) is the absolute dense volume of the liner. The relative densities are calculated based on those results.

2.3. Microstructure Characterization

The specimens were cut from the liners, polished to make samples for characteristic. The scanning electron microscope (SEM) was utilized to observe the microstructure of the specimens and the energy dispersed spectroscopy (EDS) attached to SEM was used to determine the composition in the specimens. The X-ray diffraction (XRD) performed on some relatively smooth surfaces of the specimens. The transmission electron microscopy (TEM) and the scanning transmission electron microscopy (STEM) were used to characterize more details on the microstructure. The TEM specimens were prepared by FIB after mechanical polishing.

2.4. Penetration test

To use the concrete instead of the rock mass for the penetration tests. All targets used in the penetration test were concrete targets (target size: 10m × 10m × 1m, GB/T50107 – 2011 ). All liners were tested under the same conditions including compositions of explosive, geometric dimension of explosive, and blasting height.
3. Result and discussion

3.1. Penetration performance

In order to investigate the penetration performance of series of Fe-Al-Bi alloys with differences in Fe, Al and Bi contents, the SCLs with different Fe-Al-Bi contents alloys are subjected to explosive loading. Figure 1 shows the detail of the penetration channels penetrated by the Fe-Al-Bi jets. According to the experimental experience, Bi content is fixed at ten percents, and Fe content and Al content are changed in relative proportion as 3:7, 4:6, 5:5, 6:4, 7:3. A conclusion could be drawn from the Figure 1: taking given concrete as the penetration target, with the increase of relative content of Fe and the decrease of relative content of Al, penetration depth gradually grew and diameter gradually reduced. Normally, in the process that SCL is collapsed into jet, traditional compact single material SCL forms metal jet. While, Fe-Al-Bi alloy SCL formed high-energy particle jet when accelerated along the axis of symmetry by the high pressure of the detonating high explosive charge[11]. On one side, in the process of collapsing, under high temperatures and high pressures, Al turns actively that easily react with oxide, salt and other materials: taking their Oxygen elements. Compared with traditional penetration test, Fe-Al-Bi alloy SCL penetration tests have one more reaction between the target and the jet, aggravating the penetration reaction and enlarging penetration diameter. On the other side, in the high-energy particle jet, Al is the carrier and mixed with Fe and Fe-Al compounds. Fe’s high density resulted in penetration depth increased. As it is known that the higher density of the original material, the deeper of the penetration depth. Hence, with the increase of Fe content, the penetration depth increased. Meanwhile, because of the low melting point of Bi, at the beginning of jet formation, the jet is the mixture of liquid Bi and solid-liquid mixed state of particles Fe, Al and Fe-Al, which ensures the continuity of the jet. Along with continuous ejection of the jet, the temperature of jet is rising. Strong reaction of Bi generates amount of heat and gas, and secondary explosion effect accompanied. Compare with traditional jet, the Fe-Al-Bi jet is no longer slender jet: it forms a high temperature and high pressure region, which is helpful to improve the penetration performance of the SCL. At last, there is no slug after the reaction between high-energy particle jet and the target that the penetration aperture is clean. According to the data above, given consideration to penetration in both depth and diameter, the best proportion of alloy is 36Fe-54Al-10Bi (wt.%, Fe-Al-Bi) alloy.

Apart from material content, 36Fe-54Al-10Bi (wt.%, Fe-Al-Bi) alloy SCL material density was also researched. Under different pressing pressure, No.1, 2, 3, 4, 5 SCLs that differed in density were prepared. Their respective densities were verified as 79.7%, 83.3%, 88.1%, 93.1%, 99.2%. With
certain charge equivalent and certain bursting height, the 4 SCLs were experimented on the penetration targets that were prepared identically. The penetration results were as Figure 2:

![Figure 2. Penetration results of the SCLs with different density.](image)

A conclusion can be drawn from the Figure 2: with the increase of SCL material density, the penetration depth grows and the diameter enlarges. But when the density is above 93.1%, the penetration depth and diameter decline. It is because in the process that SCL is collapsed into jet, the interspaces inside alloy material allow the jet to expand. Instant collapse releases heat that the jet temperature rises obviously[12]. Meanwhile, since Bi has low melting point and boiling point, high temperature jet intensifies Bi’s fusion and gasification, thereby the jet expands. Furthermore, with more interspaces, the jet temperature rises faster, and the jet expands faster, so penetration depth becomes lessened and the diameter becomes enlarged. But when the density is below 93.1%, the porosity is too high to form the stable jet. So the penetration depth and diameter go down.

When the 36Fe-54Al-10Bi (wt.%, Fe-Al-Bi) SCL is collapsed into jet, the material itself has following influence on penetration performance. Firstly, since the interspaces among the 36Fe-54Al-10Bi (wt.% Fe-Al-Bi) SCL is also collapsed under high temperature and high pressure at 107s-1 strain rate, the jet temperature is much higher than that of compact material SCL. Secondly, the 36Fe-54Al-10Bi (wt.% Fe-Al-Bi) SCL has certain amount of Bi material whose melting point and boiling point are low. Bi’s melting and partially gasifying cause jet to expand. The expanded jet would kind of lessen penetration depth but prominently enlarge penetration diameter. Thirdly, high-energy particle jet has good continuity that could avoid poor extensibility break-ups, so it is beneficial to penetration depth when react with the target. Fourthly, Fe and Al has violent combination reaction under high temperature and high pressure. It endows the jet with more energy. Lastly, when the jet is reacting with the target, high-energy particle jet offered energy to the reaction between Al and the target. The reaction turns more efficient and the penetration performance is improved.

3.2. Microstructure characterization
Figure 3 shows the SEM image of the Fe-Al-Bi alloy. The white areas are Fe particles, and the dark areas are Al. And the grey areas is the transition areas, which is the compound of Fe and Al. This image shows the SEM micrograph of the Fe-Al-Bi alloy with line scanning and it focused on the Fe and Al only. It can be seen from figure that Al is the matrix of the alloy, Fe is evenly distributed on the matrix and Bi only exists in the gaps of Fe and Al particles. There are even intermediate phase transition layers around the Fe particles. We can discover by the line scanning: in the process of scanning from Al matrix to Fe particles, at the start section, the content of Al is high and the content of
Fe is scarcely. When scanning through the transition area, the content of Fe increases significantly as the content of Al decreases. Moreover, there is a plateau for both Al and Fe. After the transition area, when the scanning arrives at the Fe particle area, the content of Al reduces to zero, and the content of Fe increases to full.

Figure 3. SEM image of the Fe-Al-Bi alloy.

Figure 4 illustrates the XRD pattern of the Fe-Al-Bi alloy. It is evident that the alloy phase only includes Al, Fe, Fe₃Al, and Bi in which (200), (220), and (222) peaks of Al are superimposed on (110), (200), and (211) peaks of Fe. Only (111) and (311) peaks of Al are unaffected. So that, the microstructure of the alloy is that Al is the matrix, Fe particles covered by Fe₃Al distribute evenly on the matrix and the Bi exists in the gaps of Fe and Al particles. The core of the particles is Fe that has good ductility and toughness and the shell is Fe₃Al that has high hardness. From the comparative test result, we can draw a conclusion that the penetration performance of Fe-Al-Bi SCL is better than that of others material whose particles are pure Fe or Fe₃Al. Because compared with the pure Fe particles, in the process of penetrating concrete target, Fe-Al-Bi SCL particles have harder shell that cannot have plastic deformation easily. So that in penetration process it has better performance. And compared with pure Fe₃Al particles, in the process of penetration with concrete target, Fe-Al-Bi SCL particles have better ductile and tough cores that cannot easily break into pieces. Therefore, the particles with Fe core and hard Fe₃Al shell can easily transfer kinetic energy and penetrate brittle concrete targets. Fe particles covered with certain amount of hard Fe₃Al have better performance in penetration depth and diameter with concrete targets.
Figure 4. XRD pattern of the Fe-Al-Bi alloy.

Figure 5. Microstructure of the Fe-Al-Bi alloy: (a) TEM image (b) STEM image (c) selected area diffraction pattern (d) schematic diagram of the indexed selected area diffraction pattern.
The material microstructure characterized by TEM. Figure 5(a) shows a TEM bright-field image taken from the specimen. There is an obvious twin band, whose size is 100nm, in grain. Twin band does not exist in normal Fe₃Al specimen. This is deformation twin band from hot pressed sintering. Figure 5(b) shows clear twin band in STEM image. The presence of DO3 phase could be confirmed. Figure 5(d) is the schematic diagram of the indexed selected area diffraction pattern from the DO3-ordered Fe₃Al matrix. [111] represents the DO3 structure of Fe₃Al and the B2 structure is represented by [200]. In Figure 4(c), [111] is clear and [200] is unclear, which indicates that the DO3 structure of Fe₃Al is the main structure and the B2 structure almost does not exist.

Figure 6 show the XRD result of the milled powder. It can be seen that the diffraction peaks of the milled powder has the tendency of shifting to lower angle, that means the lattice parameter increased. The calculated lattice constant is 0.28726nm, a little bit larger than the lattice constant of Fe 0.28695. It indicates the diffusion of aluminum into the iron lattice, resulting in the increase of iron lattice constant. Part of aluminum and iron become solid solution. At same time, during the mechanical alloying process, the plastic deformation of powders leads to fine grain size of the powder and increases the grain boundary strain energy. For the XRD, it leads to widening of diffraction peak and reducing of diffraction intensity.

3.3. Microstructure characterization
During the mechanical alloying process, with the ball milling collision, iron and aluminum powders turn into sheet structure. Then extensive cold welding process takes place. Sheet structures component are welded together and transformed into lamellar composite structure. After some time in the ball milling, the composite powders are further refined and layer spacing are decreased. The powders begin to be alloyed. Alloying is affected by many factors. For example, the heating effect caused by ball milling; the proliferation of diffusion path caused by plastic deformation defects; and the diffusion distance decrease caused by the refinement of the lamellar structure. All of them have benefits to the alloying. The Fe-Al powders, during the milling process excited by mechanical alloying, are in a high-energy state and created conditions for the follow-up transformations.

From the thermodynamic perspective of view to analysis:
Using the Miedema model[13], for a binary alloy composed of a transition metal and a non-transition metal, its formation enthalpy is:
\[ \Delta H = \frac{2Pf_{AB}(C_AV_A^{2/3} + C_BV_B^{2/3})}{(n_{ws})_A^{1/3} + (n_{ws})_B^{1/3}} \cdot [-((\Delta \phi)^2 + \frac{Q}{P}(\Delta n_{ws})^{1/3} - \frac{R}{P}] \]  

(1)

where \( C_A, C_B \) are the respective atomic percentage of elements A and B. \( V_A, V_B \) are the Mole Volume.

\( f_{AB} \) is defined as the atom concentration function, which can be divided into two situations. One is ordered \( \text{Fe}_3\text{Al} \), the other is disordered \( \text{Fe}_1\text{Al} \).

Based on above thermodynamic model to calculate the formation enthalpy and the free energy of Fe and Al. In testing the temperature of ball milling pot, metal temperature increased 75K, so the calculating temperature was 350K. Parameters were as Table 1:

| element | \( n^{1/3}/\text{cm}^3 \) | \( \phi/V \) | \( V^{2/3}/\text{cm}^2 \) | Tm/K | hm/KJ·mol⁻¹ | K/10¹¹N·m⁻² | G/10¹⁰N·m⁻² |
|---------|----------------|-------------|----------------|------|-------------|-------------|-------------|
| Fe      | 1.77           | 4.93        | 3.7            | 1808.5 | 15.308      | 1.698       | 0.816       |
| Al      | 1.39           | 4.20        | 4.64           | 933   | 10.67       | 0.752       | 0.262       |

During mechanical alloying, the motive force for a state variation or a solid state reaction is initiated by mechanical energy. Binary powders get repeating impact, compression and shear by the ball in milling. The defects inside the crystal are increasingly cumulated, that result in the energy of lattice distortion increasing. Simultaneously, grain refinement lead to grain boundary volume increase violently and interfacial energy increase constantly. In addition, for the ordered intermetallic compound, the antisite defect caused by mechanical alloying could lead the disorder energy to a high level. Therefore, there are three main forms of energy increase: the lattice distortion energy caused by crystal defects, interfacial energy caused by grain refinement, and disorder energy caused by antisite defect.

The contribution of grain refinement for free energy is:

\[ \Delta G = \frac{3rV}{D} \]  

(2)

where \( V \) is alloy Molar Volume, \( r \) is boundary energy. The mechanical alloyed nano-crystalline contains a large amount of grain boundary regions. Most of them are consisted of random, large angle grain boundary. So the boundary energy \( r=5.5\times10^{-11}\text{J/cm}^2 \). \( D \) is mechanical alloyed grain diameter. And it can be calculated by the XRD data that \( D=15\text{nm} \). So the interfacial energy increment due to grain refinement is \( \Delta G=3.21\text{KJ/mol} \). It can be seen that grain refinement cannot provide enough energy for \( \text{Fe}_3\text{Al} \)'s transition.

The lattice distortion energy caused by dislocation could be roughly estimated: taking it as iron grain refinement, lattice distortion, and diffusion of aluminum atoms into iron lattice. So the iron lattice is used in the calculation model. The dislocation strain energy of unit length is:

\[ E = KD\sigma^2 \]  

(3)

Where \( K \) is constant, and for metal \( K=1 \). \( G \) is elastic modulus, and take \( G=81.6\text{Gpa} \) for iron. The Burgers vector length of BCC structure lattice dislocation is \( \sqrt{3a}/2 \), and \( a \) is the lattice constant. Iron’s lattice constant is \( 0.2860\text{nm} \). Strain energy of dislocation for per unit length is \( 5\text{nJ/m} \). The dislocation density of plastic deformed metal is \( 1012-1014\text{cm}^2 \). To take the dislocation density as \( 1013\text{cm}^2 \), so the energy density in the crystals due to dislocation is \( 0.5\text{KJ/cm}^3 \). It has been known that iron’s Mole Volume is \( 7.16\text{cm}^3/\text{mol} \), so the free energy increment due to dislocation is \( 3.58\text{KJ/mol} \). The energy increment due to grain refinement and dislocation is \( 6.79\text{KJ/mol} \).

Dynamics of phase evolution:
Fe-Al mixed powders from a simple mixture into a solid solution must be accompanied by the atomic level material migration that is controlled by the diffusion process. According to the Arrhenius equation:

\[ k = Ae^{-Ea/RT} \]

Where \( R \) is the Mole gas constant, \( T \) is the thermodynamic temperature and \( E_a \) is the activation energy.

The activation energy is analyzed by combining the characteristics of high energy ball milling. During the ball milling, there are lots of defects. The diffusion of aluminum atoms into the iron lattice is determined by the vacancy mechanism. The activation energy consists of vacancy formation energy \( Q_f \) and migration energy \( Q_m \). Because the formation of vacancies is dominated by high energy ball milling rather than thermal excitation a large number of vacancies and defects in lattice are introduced by high-energy ball milling. So that the vacancy formation energy \( Q_f \) is negligible. The activation energy consists of the migration energy \( Q_m \) only. Therefore diffusion coefficient \( k \) increased while activation energy significantly reduced. So in high energy ball milling process, the reduction of activation energy leads to the enhancement of diffusion effect, which is the main approach to initiate solid phase transformation.

With the increase of milling time, the density of defects increased gradually. Defects play a major role in the process of homogenized diffusion during high-energy ball milling. Many free surfaces are formed by crushing the particles. While grain refinement formed a large number of grain boundaries. Thus formed a large number of defects within the grain, so as to provide fast diffusion channels of atoms, greatly reducing the activation energy of solid reaction, and increasing atomic diffusion rate. The solid-state phase transformation happened in normal temperature instead of the thermal activation state under high temperature.

4. Conclusions
The Fe-Al-Bi alloy SCL is prepared by mechanical alloying process and hot pressing sintering process for concrete or rock targets. Compared with the traditional single metal SCL, after penetration, Fe-Al-Bi alloy SCL has no rod slug residue and penetration channel has no blockage. Since the low melting point of Bi, the jet has good continuity and is easy to expand. So the penetration performance can be improved. Since the amount of Al, when the jet is reacting with the target, the reaction between Al and the target will improve the penetration depth and penetration diameter. The particles made of ductile iron core and hard Fe₃Al shell in ball milling and hot pressed sintering process also benefit penetration performance.

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