Analysis on the Characteristics of the Damage Area around the Shrapnel Penetration Part of Titanium Alloy Skin of Aircraft

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Abstract. The paper analyzes the characteristics of the damage area around the shrapnel penetration part of titanium alloy OT4 skin of the aircraft during the live ammunition damage test. The skin of a bullet hole in a certain model of aircraft is cut as a test sample. Through micro-hardness (DPH), metallographic structure (OM), microstructure (SEM), and microscopic analysis of energy spectrum (EDS), it makes statistics and analyzes the microstructure of damage area of skin, verifies the damage scope and influence area of the shrapnel penetration area, determines the damage repair boundary around the missile shrapnel penetration area, and lays a theoretical foundation for carrying out in-situ growth repair of titanium alloy structure based on micro-arc additive technology in future.

1. Introduction

According to the research conclusion [1] of GF-A00555292G report, when the aircraft and missile meet in the process of combat, the aircraft generally flies at 300-800m/s. The flight speed of anti-aircraft air-defense missile is generally around 2000m/s, the velocity of the fragments relative to the projectile body after the missile explosion. Therefore, when the missile fragments rendezvous with the aircraft structure, it may create the maximum relative collision velocity for nearly 2000m/s-5000m/s. Under such high-speed collision conditions, the aircraft structure will generate extremely high pressure and temperature at the damage area [2-3].

Due to the impact that the pressure is high and far greater than the strength of the material, the material at the point of collision can be treated as a fluid. If the speed is not very high and the fragments do not break, the impact of the fragments on the aircraft structure is as if stones hit mud, and the holes formed are typical shape of “mud pits” ; if the speed is higher, the fragmentation of fragments and target plates occur during the collision, resulting in a high temperature debris cloud and dense honeycomb damage to the underlying structure [4-5]. The high impact temperature may cause the material to melt, but such melting is generally generated in the isentropic unloading process after the fragments pass through the structure. That is because in the adiabatic collision loading stage, the pressure in the material is very high and the melting point increases sharply, so the material is not easy to melt. However, in the unloading process after the fragments pass through the structure, the melting
point of the material decreases rapidly with the pressure, but the temperature drops relatively slow, resulting in the so-called unloading melting phenomenon [4-5].

Therefore, based on the ground static explosion damage test data of missile warhead, the skin of a bullet hole in a certain model of aircraft is cut as a test sample; this paper analyzes the microstructure of penetration area of live ammunition damage test on titanium alloy structure by micro means, and analyzes micro-topography, phase, and micro-hardness of penetration area of live ammunition damage test on titanium alloy structure so as to lay a foundation for polishing treatment of micro-arc cladding bullet holes and notches in later stage.

2. Test preparation

According to the ground static explosion damage test of the missile warhead, the fragment material of the warhead is structural steel, and the relative velocity of the fragment is 3000m/s. The impact pressure and temperature of the aircraft titanium alloy structure under the impact of high speed fragments are calculated to be 57GPa and 1030K. The appearance morphology of the aircraft titanium alloy OT4 skin shrapnel penetration area and the sampling area for test observation are shown in Figure 1.

![Test sample A](image1.png)
![Test sample C](image2.png)

Figure 1 The appearance morphology and sampling area of the bullet hole damage area of aircraft skin

3. Test sample preparation process

For the test sample preparation process, it goes through the steps of cutting—inlay—grinding—polishing—corrosion and other steps. The sample preparation process strictly follows the requirements of HTKJ-0360-03 High Magnification Personnel Operating Instruction. The sample preparation process is shown in Figure 2.

![Physical picture of test sample A after cutting](image3.png)
![Physical picture of test sample C after cutting](image4.png)

Figure 2 The sample preparation process
4. Sample test analysis

4.1 Micro-hardness analysis
The micro-hardness test method is carried out in accordance with GB/T4340.1-2009 and ASTM E384. The model of hardness meter is TUKON 1102. See Figure 3 and 4 for the sampling location and measurement process of micro-hardness.

4.1.1 Data statistics
Number test sample A and C of the shrapnel penetration area, and cut 10x10mm test blocks from the damage area. Then, find the change rule of its micro-hardness from the damage area to the skin core by 300g load at an interval of 0.500mm for 15s. See Table 1 for specific data statistics.

Table 1 Statistics of the micro-hardness of the damage area of the aircraft skin in the shrapnel penetration area

| Test sample Number | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|--------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| A1                 | 307| 286| 288| 281| 290| 293| 273| 283| 288| 286| 276| 285| 289| 275| 286| 289| 294| 282| 291| 294|
| A2                 | 287| 277| 291| 295| 274| 263| 258| 268| 272| 255| 263| 258| 268| 272| 255| 263| 258| 268| 272| 255|
| A3                 | 294| 273| 266| 275| 272| 285| 264| 269| 254| 288| 272| 282| 254| 288| 272| 282| 254| 288| 272| 282|
| A4                 | 270| 270| 270| 270| 270| 270| 270| 270| 270| 270| 270| 270| 270| 270| 270| 270| 270| 270| 270|
| C1                 | 262| 262| 262| 262| 262| 262| 262| 262| 262| 262| 262| 262| 262| 262| 262| 262| 262| 262| 262|
| C2                 | 263| 263| 263| 263| 263| 263| 263| 263| 263| 263| 263| 263| 263| 263| 263| 263| 263| 263| 263|
| C3                 | 259| 259| 259| 259| 259| 259| 259| 259| 259| 259| 259| 259| 259| 259| 259| 259| 259| 259| 259|
4.1.2 Data analysis of test sample A

ORIGIN data processing software is used to analyze A1, A2, A3, A4 data of aircraft skin of sample A at the shrapnel penetration area. The micro-hardness decreases from the edge of the bullet hole to the point far away from the bullet hole. The difference between the maximum value and minimum value of A1 is 32HV0.3; the maximum value occurs at the first point on the edge of the bullet hole; and the minimum value occurs 3.5mm from the edge; the average value is 287.5HV0.3; the first point 307HV0.3 differs from the average data by 19.5HV0.3; the tensile strength varies about 70MPa according to the conversion of ASTM A370. The difference between the maximum value and minimum value of A2 is 37HV0.3; the maximum value occurs 7mm from the edge of the bullet hole and the minimum value occurs 7.5mm from the edge; the average value is 274HV0.3; the first point 287HV0.3 differs from the average data by 13HV and strength by 40MPa. The difference between the maximum value and minimum value of A3 is 34HV0.3; the maximum value occurs 6mm from the edge of the bullet hole and the minimum value occurs 5.5mm from the edge; the average value is 273HV0.3; the first point 284HV0.3 differs from the average data by 11HV0.3 and strength by 40MPa. The difference between the maximum value and minimum value of A4 is 30HV0.3; the maximum value occurs 2.5mm from the edge of the bullet hole and the minimum value occurs 3mm from the edge; the average value is 284HV0.3; the first point 294HV0.3 differs from the average data by 10HV0.3 and strength by 30MPa.

4.1.3 Data analysis of test sample C

Analyze C1, C2, and C3 data of aircraft skin of sample C at shrapnel penetration area. As shown in Figure 5: the micro-hardness decreases from the edge of the bullet hole to the point far away from the bullet hole. The difference between the maximum value and minimum value of C1 is 42HV0.3; the maximum value occurs 1.5mm from the edge of the bullet hole and the minimum value occurs 5.5mm from the edge; the average value is 260HV0.3; the first point is basically consistent with the average strength. The difference between the maximum value and minimum value of C2 is 36HV0.3; the maximum value occurs 2mm from the edge of the bullet hole and the minimum value occurs 4mm from the edge; the average value is 253.5HV0.3; the difference of tensile strength between the first point 262HV0.3 and the average value is about 30MPa. The difference between the maximum value and minimum value of C3 is 44HV0.3; the maximum value occurs 8mm from the edge of the bullet hole and the minimum value occurs 1.5mm from the edge; the average value is 254HV0.3; the difference of tensile strength between the first point 274HV0.3 and the average value is about 50MPa.

4.2 Analysis of metallographic structure

4.2.1 Sample morphology

The paper carry out microstructure observation on test sample A, and C, and conduct ASTM E407 in accordance with corrosion. The ratio of corrosive is HF: HNO₃ : H₂O=1: 2: 7. The macroscopic morphology of the test sample after corrosion is shown in Figure 4.

![Figure 4 Sample morphology after corrosion](a) A after corrosion  
(b) C after corrosion
4.2.2 Microstructure observation
Observe the test sample A and C after corrosion under metallographic microscope. The microstructure of test sample A is mainly formed by dual phase equiaxial structure. The damage area of A is dominated by fine crystals. The maximum damage layer of A is about 1.4mm. There are obvious adiabatic shear bands in the damage area of C. The maximum damage depth area of C is 1.14mm. Adiabatic shear band refers to a narrow band region with high shear deformation height regionalization under high strain rate loading conditions, such as high speed forming, forging, extrusion, cold forging, and cutting, etc. Its width is narrow, normally at μm level. It can generate shearing strain of 10-10² magnitude in ASB and its temperature rise can reach 10²-10³K. Moreover, due to the presence of a matrix with a cold temperature around it, the materials in ASB have to undergo fast cooling rate (>10⁵), and the entire deformation time is very short. In such a short time, most (about 90%) of the deformation work is converted into heat without enough time for diffusion, so the deformation process at such a high strain rate is approximately considered as an adiabatic process. Because adiabatic shear band is a kind of special local instability phenomenon, which is closely related to material failure, so the occurrence of adiabatic shear band in material components means the decrease or loss of material bearing capacity. Therefore, it is considered as a precursor of material failure.

4.3 Scanning electron microscope analysis

4.3.1 Scanning electron microscope lofting information
For the test sample after metallographic observation, the microstructure of the sample is further observed under ZEISS EVO18. The specific lofting steps are shown in Figure 5.

(a) Stick conductive adhesive   (b) Stick to working stage                 (c) Fixed base                 (d) Close vacuum chamber

Figure 5 Scanning electron microscope lofting steps

4.3.2 Scanning electron microscope microstructure analysis
Further observe the microstructure of the sample under ZEISS EVO18, under the observation of scanning electron microscope (SEM), the microstructure of test sample A and C change from damage area to matrix structure, from fine to coarse, but both of them are α+β dual phase structure and has not reached to phase transition state; the structure is etched and the shape of local primary α phase is long stripe due to poor electrical conductivity and poor sharpness of photos.

4.4 Micro-area energy spectrum analysis
Under scanning electron microscope of ZEISS EVO18, make EDS micro-area energy spectrum analysis on hole edge and core of test sample A and sample C.
According to the micro-area energy spectrum analysis of test sample A and C, the micro-area energy spectrum alloying elements of test sample A and C are mainly Ti, O, Ba, Al, and Mn, etc. The main elements are titanium alloy OT4 matrix elements, which contain a small amount of impurity elements without significant difference. Because titanium alloy is more active, it forms dense oxide film in the air to prevent further corrosion, resulting in high surface oxygen content.

4.5 Comprehensive analysis
According to the analysis of the micro-hardness test results of shrapnel damage area of two different
types of aircraft skin in test sample A and C, the micro-hardness from the edge of the bullet hole to the point far away from the bullet hole decreases. The hardness of the damaged deformation area around the bullet hole is generally higher than the average hardness value of the matrix. By converting to tensile strength, the maximum difference value is 165MPa. The microstructure is α+β dual phase structure. The shrapnel damaged area may crystallize, resulting in relatively small structure, local thick matrix structure and long primary α phase. Because shrapnel hits the skin of the aircraft at high speed and makes the skin to bend and deform, the titanium alloy skin around the bullet hole deforms rapidly under bending load. Titanium alloy is adiabatic sensitive material. At high deformation rate, due to poor thermal conductivity of titanium alloy, adiabatic shear band structure is easy to occur in the high speed forming process, that is, micro-cracks, white light layer and voids around the bullet hole. By observing microstructure under scanning electron microscope, it is similar to metallographic structure, which shows the characteristics of etching morphology and is consistent with microstructure. Micro-area energy spectrum (EDS) is mainly composed of matrix elements, such as Ti, O, Ba, Al, and Mn, etc. and a few impurity elements, and no obvious abnormal phenomenon is found.

5. Conclusions
By analyzing the micro-hardness (DPH), metallographic structure (OM), microstructure (SEM), and micro-area energy spectrum (EDS) of shrapnel damage area of aircraft skin in sample A and C, this paper comes to the following conclusions:

(1) The micro-hardness from the edge of the bullet hole to the point far away from the bullet hole decreases. The converted tensile strength of the bullet edge is generally higher than the matrix, and the maximum difference value is 165MPa;

(2) According to metallographic structure (OM) observation, the maximum damage layer of A is about 1.4mm, and the maximum damage depth is 1.14mm. Adiabatic shear band structure is common in the damage deformation area. The microstructure of the damage area is relatively small, α+β dual phase structure. The local matrix structure is large and there is long primary α phase. The dynamic recrystallization may exist in aircraft skin during deformation.

(3) The microstructure of sample A and C changes from damage area to matrix structure, from fine to coarse, but both of them are α+β dual phase structure and has not reached to phase transition state; the structure is etched and the shape of local primary α phase is long stripe.

(4) Micro-area energy spectrum (EDS) is mainly composed of matrix elements, such as Ti, O, Ba, Al, Mn, and O, etc. and a few impurity elements, and no obvious abnormal phenomenon is found.

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