**Study on the Properties and Fracture Splitting of Cast Steel Matrix Composites**

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Study on the Properties and Fracture Splitting of Cast Steel Matrix Composites

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Abstract

To break through the limitations of fracture splitting materials of connecting rods, a bimetallic compound as a fracture splitting material was studied. In this experiment, the bimetallic sample was produced by investment casting; interface performance tests and splitting tests were conducted. The results showed that when the casting temperature of 0.25wt%C cast carbon steel was 1600°C, the preheating temperature of T10A was 500°C, and the thickness of T10A in the range of 2 mm to 3 mm. The 0.25wt%C cast carbon steel and T10A were fully combined in the interface. The appearance of the fracture zone was a flat cleavage fracture, which would facilitate the meshing of the cracked surface if the specimen were assembled and improve the quality of fracture splitting.

Key Words: Bimetallic compound; Cast; Connecting rod; Fracture splitting; Properties
1 Introduction

Unlike the machining of a composition plane between a rod and a cap for a traditional connecting rod, the making of a connecting rod by fracture splitting adopts controllable cracking to separate the cap from the rod, which greatly simplifies the manufacturing procedures of the composition plane and bolt holes (Gu et al., 2005). Two symmetrical notches with the same shape and size are first made on the inner side of the connecting rod’s big end hole, forming the starting point of splitting cracks out of stress-concentration effect. Then, applying a radial force to the big end hole of the connecting rod, resulting in the big end brittlely fracturing from two notches. At last these two split parts are assembled with bolts on a special equipment so as to perform later processes (Kou et al., 2001; Kou et al., 2004). Fracture splitting offers a list of remarkable merits, including favorable product quality, low manufacturing cost, high production efficiency, frugal material usage rate, and economical equipment investment. However, fracture splitting materials must have the following characteristics: light weight, high fatigue strength, appropriate brittleness, and low plasticity (Weber 1993). Generally, the tensile strength of the material of the cracking connecting rod is required to be 900MPa - 1050 MPa, the yield strength is higher than 520 MPa, and the impact toughness is 4J · cm^{-2} - 8J · cm^{-2}. Therefore, fracture splitting materials are limited to metals made using powder metallurgy, nodular graphite cast iron, malleable cast iron, and so on. Even with suitable materials, the production process typically encounters numerous problems, such as fracture splitting only one side, and dregs (Kou et al., 2011; Kou et al., 2017). A problematic workpiece is one that does not permit the cap and rod to reunite accurately when it is reassembled.

Brittle materials for fracture splitting are subjected to strict requirements, which dictate that aluminum alloys, titanium alloys, 40Cr, and some other materials cannot be subjected to fracture splitting for the manufacture of connecting rods (Zhang et al., 2011;
Liu et al., 2013; Yang et al., 2014). In addition, common brittle materials also exhibit splitting deformations, pyrolysis, surface migrations, split branching, dregs, explosive ports, and other defects (Fukuda and Eto, 2002; Liu et al., 2010; Zhang et al., 2011). To solve the aforementioned problems, this paper presents a process for manufacturing connecting rods from two materials with different mechanical and microstructural properties. The method is to use a material with high strength and toughness that is applied to the main material of the connecting rod, and a brittle material that is placed in the fracture zone. With this method, the component can be split at the fracture zone, without any substantial ductile deformation. After splitting, the cap portion can be reunited with the rest of the component by bolts, and thus a connecting rod can be obtained by double metal composite fracture splitting (Hui et al., 2015; Kachanov et al., 2016). The bimetallic connecting rod enlarges the application scope of the connecting rod’s material, therefore, the ordinary carbon steel materials are available to manufacture connecting rods. On the one hand, the brittleness occurs in the cracking zone during fracture splitting, reducing the deformation of the big end hole, and meets the requirements after assembly. On the other hand, the fracture splitting of bimetallic connecting rod can also reduce the offset of the fracture surface, split branching, dregs, explosive ports, and other defects, and greatly improve the success rate of fracture splitting.

This paper studies how to use the investment casting process to manufacture double steel composites suitable for splitting to make connecting rods. Through analysis and experiments, a suitable fracture splitting material and bimetallic investment casting technology of the connecting rod have been selected. These materials and techniques ensure that the cracked material does not oxidize, that its thermal fusion with 0.25wt%C cast carbon steel at the interface can be effective, and that this effective thermal fusion meets requirements of interface performance and follow-up processing. The follow-up processing, includes heat treatment, forging, and fracture splitting. This paper focuses on
the applicability of composite bimetallic investment castings for fracture splitting technology. The proposed composite bimetallic process is a new and innovative process. It provides a new method to break through the limitations of fracture splitting materials.

2 Experimental

2.1 Preparation of bimetallic composite material

Connecting rods made by fracture splitting must be composed of suitable materials. They require both fatigue resistance and impact resistance, and also must have sufficient strength, stiffness, and favorable toughness; it is challenging to find a single metal material that has all of these features. Through composite investment casting technology, materials with favorable toughness and comprehensive mechanical properties can be selected as the main material, and a fracture splitting material with high strength and high brittle fracture suitability can be selected for the fracture region. In the preparation of a composite sample, it is necessary to ensure that the two materials are sufficiently thermally fused at the interface, and still have sufficient thickness of fracture splitting material for splitting in the fracture region.

The main material used in this experiment is 0.25wt%C cast carbon steel, which has favorable plasticity and toughness, its strength and hardness are also very good; the fracture splitting material is T10A, which has the characteristics of high hardness and high brittle fracture suitability. The chemical compositions of the two materials are shown in Table 1.

Throughout the investment casting process, reasonable process parameters are critical. The thickness of the fracture splitting material has to be within a certain range, which must ensure that the fracture splitting material can be fused with 0.25wt%C cast carbon steel well, and also have adequate thickness to be split and be appropriate for subsequent forging. The sand molds should be calcined at a certain temperature for a
period of time, so that the shell can have favorable air permeability, and be strong. The fracture splitting material must also undergo a preheating treatment, which ensures that when 0.25wt%C cast carbon steel is poured against it in liquid form, no quench solidification and bubbles occur at the interface. The 0.25wt%C cast carbon steel requires a high pouring temperature, which provides enough heat for the two materials to fusion bond fully at the interface. The final insulation treatment is also vital, not only to prevent any oxidation of the interface, but also to ensure the full fusion of the two materials.

The simulation of the casting process was made by ProCAST (Qian 2016; Qian et al., 2016). The casting method of the bimetallic connecting rod is designed as the side injection, and the side injection casting system is shown in Figure 1. Then the grid is divided and repaired, and the thickness of the shell is 5mm in the MeshCAST module. The formed shell is shown in Figure 2. Then the properties of materials are set. The type of the body material is Alloy, and the stress model is Linear-Elastic. The type of the fracture splitting material is Mold, and the stress model is Rigid. The material of the shell is Silica Sand, the type is Mold, and the stress model is Rigid. Then the contact types are all set to COINC in the interface conditions. The casting temperature of the body material is 1600°C, the preheating temperature of the fracture splitting material is 500°C, the temperature of the shell is 1200°C. The cooling condition is Air-Cooling. The Fill Time is 3s and the casting velocity is automatically calculated to be 48.6162 mm/s. The running parameters are set eventually. The pouring type is Gravity Filling, the number of ending steps (NSTEP) is 5000, and the ending temperature (TSTOP) is 1420°C.

It is crucial to select the pouring temperature of the 0.25wt%C cast carbon steel, the preheating temperature of the T10A, and the temperature of the shell baking for the casting process (Lazarus 1960). Orthogonal simulation experiments were carried out for the following parameters (Chen and Lin 2017): pouring temperature (1580°C, 1600°C, 1620°C), preheating temperature of the cracking material (400°C, 500°C, 600°C), preheating temperature of the mold shell (1100°C, 1150°C, 1200°C). The measured
indexes were the maximum shrinkage porosity, maximum effective stress and maximum deformation. When the pouring temperature is 1600°C, the preheating temperature of the cracking material is 500°C and the preheating temperature of the shell is 1200°C, the connecting rod is in a good condition. There is no shrinkage in the main body of the connecting rod. There is a small amount of shrinkage in the pouring cup and the sprue, which can be seen in Figure 3. The maximum effective stress is 373.9MPa, which appears at the inner gate. The maximum deformation is 0.0341cm, which is located at the bottom of the sprue. So the parameters above meet the requirements of the casting process (Qian 2016). The relationship between temperature and time at the lowest temperature of the fracture splitting material was shown in Figure 4. It showed that when the casting temperature was simulated at 1600°C and the preheating temperatures of T10A and the shell were simulated at 500°C and 1200°C, the minimum temperature of the cracking material was simulated reached 1437°C and keeps higher than the solidus temperature (1430°C) for more than 60s, so that the two materials can be fused and bonded together.

To determine the thickness of T10A, the volume ratio of liquid 0.25wt%C cast carbon steel to T10A in the mold was simulated. When the volume ratio was high, the simulation showed the two materials melt bonding easily; however, an excessively high volume ratio leads to excessive melting of T10A, resulting in deformation of the fracture splitting material. ProCAST was used to simulate the relationship between temperature and time at the lowest temperature spot in the fracture splitting material under different volume ratios. The results are shown in Figure 5. When the volume ratio was 12, the lowest temperature spot of the T10A stayed near the melting point for nearly 30 s, which would ensure the fusion of the two materials. However, when the volume ratio was 24, the lowest temperature of T10A exceeded the solidus temperature and endured for more than 180 s; under such circumstances, T10A would melt excessively, leading to the deformation of the fracture zone. In light of the volume of the sand mold and the
simulation results, the thickness of T10A was controlled at 2–3 mm (Qian 2016). Through several physical investment casting tests, the simulation results of the aforementioned crucial parameters were repeatedly tested. Finally, the optimal process parameters were found; they are shown in Table 2.

To achieve favorable samples, some pre-treatments of the samples are essential. The critical steps are as follows. First, wax samples are made in a wax die casting machine; subsequently, they are welded to the casting system and then washed with water and dried in air. Then, slurry and sand are sprayed on the surface in turn, which needs to repeat for four times. The slurry, made of silica sol and zircon powder, and the zircon sand are used for the first time. The slurry, made of silica sol and mullite powder, and the mullite are used for the rest. And the samples are dried in air after each step. Then, dewaxing treatment is carried out in a steam oven at 150°C for 15 minutes; finally, a sand mold shell is obtained. The carbon steel is melted at a temperature of 1600°C. The sand mold is calcined to 1200°C and the fracture splitting material is preheated to 500°C. The preheating fracture splitting material is inserted into the mold quickly. The carbon steel is loaded into the sand mold; the sand mold is placed in a sand table and covered with a barrel insulator for 20 minutes, and then air-cooled. Finally, the bimetallic casting billet is obtained. The casting billet is shown in Figure 6. In the present study, the casting billet had no casting defects on its surface and had a favorable combination. The bimetallic casting sample shown in Figure 7 is made from the casting billet with electrospark wire-electrode cutting.

2.2 Detection of elemental diffusion and microstructural analysis

To ensure that bimetallic samples can be cracked at the fracture zone, the two metals must be bonded tightly, the bonding interface must be favorable, and no cracks, holes, or other defects can be permitted. Furthermore, a diffusion layer of a certain thickness must
form at the bonding interface. The thickness of the region where the carbon content is higher than 0.6% was defined as the thickness of the fracture zone. Physical measurement made by JSM-7800F scanning electron microscope showed that the thickness of the fracture zone was approximately 2.63 mm, and the initial thickness of T10A was 2 mm. This indicated that the fracture splitting material was fused with the host material sufficiently. The concentration of carbon element on both sides of the interface was scanned by scanning electron microscope. The diffusion of carbon in the interface between T10A and 0.25wt%C cast carbon steel can be seen in Fig. 8.

Figure 9 shows the microstructure of the bonding interface, which corresponds to the regions in Figure 8. Fig. 9-(a) shows the microstructure of 0.25wt%C cast carbon steel; Fig. 9-(b) shows the microstructure of the interface transition zone; and Fig. 9-(c) shows the microstructure of T10A. Figure 9 indicates that the components of T10A and 0.25wt%C cast carbon steel combined closely; mutual diffusion was observable in the interfacial area of the two materials. Fig. 9-(a) shows 0.25wt%C cast carbon steel with more ferrite and less pearlite; Fig. 9-(c) shows T10A, and has substantial quantities of pearlite. The leftmost image shows high ferrite content and low pearlite content. Considering the images from the left to the right, one can see that the ferrite content is reduced substantially, and the pearlite increase gradually in the middle and rightmost images. This means that the combination of the two metal materials was very favorable, and provided sufficient area for cracking experiments.

### 2.3 Analysis of the mechanical properties of the bimetallic sample

A tension specimen was made by wire cutting, and a tension test was carried out with a UTM4104 microcomputer-controlled electronic universal testing machine. Figure 10 shows the fractured tensile specimen; the fracture was located at the interface between 0.25wt%C cast carbon steel and the composite; the absence of any cracks indicated that the strength at the composite interface was greater than the strength of 0.25wt%C cast
carbon steel. The microhardness of the bimetallic interface was examined. The results are shown in Figure 11. The hardness value (HV) in the interfacial region increased gradually from the 0.25wt%C cast carbon steel side to the T10A side. The numerical analysis results showed that bimetallic materials were bonded tightly at the interface; the sample had high strength performance. These properties ensure that bimetallic composites of this type can withstand impacts, inertial forces, and bending forces.

3 Splitting test and characteristic analysis

3.1 Bimetallic splitting sample and test

The samples used in this experiment did not undergo any heat treatment and were made by wire cutting. The tension test was carried out with a UTM4104 microcomputer-controlled electronic universal testing machine. The upper and lower clamps of the testing machine held the two ends of the sample. The upward movement of the upper clamp applied the vertical load to the splitting zone. This method can test whether a bimetallic sample meets the requirements of connecting rod fracture splitting. The tensile specimen was designed as shown in Figure 12-(a); the intermediate black zone indicates the fracture zone. The fracture sample with a V-type cleavage groove is shown in Figure 12-(b); the opening angle was 60°, the notch depth was 0.50 mm, and the thickness of the tensile specimen was 2 mm. After the specimen was installed on the tensile machine, the stretching speed was 1 mm/min. After the tensile test, the two parts were reassembled and measured.

3.2 Coupling analysis of bimetallic sample

For the specimen with notches, during the tensile test, the crack was first generated at the preset notch and extended along the preset path to the other notch. Thereafter, under a certain horizontal force, the sample was reassembled. The sample coupling
schematic diagrams are shown in Figure 13.

As seen in Figure 13, the sample likely experienced a low-stress fracture that substantially occurred without any ductile deformation or dregs. After the pieces were reunited, no visible cracks were observed on the specimen. Related data indicate that the deformation of the connecting-rod big-end bore must not be too large; excessive deformation affects the subsequent finishing of the connecting rod. The bimetal sample extended by 0.10%, and the sample made of pure 0.25wt%C cast carbon steel extended by 0.53%. Therefore, the two sections of bimetallic sample have better coupling after splitting.

Because T10A has high brittleness, the fracture flat was almost perpendicular to the tensile stress direction, and the fracture surface in the fracture zone was relatively flat and bright, with a typical wear crystal fracture. By contrast, the fracture in the main material zone showed obvious plastic deformation, which does not meet the characteristics of connecting rod fracture splitting.

3.3 Fracture structure analysis

Figure 14 shows the macroscopic fracture of the cracking zone. The crystal face has no regular orientation. There are numerous cleavage steps. The fracture surface has high and low undulations. There are no barbs and characteristics of plastic deformation. There are also no small fragments. The fracture structure meets the brittleness requirements of fracture splitting and the assemble requirements after cracking.

Figure 15 shows the microstructure of the fracture surface shown in Figure 14. As seen in Fig. 15-(a), the fracture surface was crystalline and contained numerous cleavage steps formed by the intersections of the cleavage planes. The portion of Fig. 15-(a) marked with a red rounded rectangle is shown at a higher magnification in Fig. 15-(b). The line shapes of the fracture shown in Fig. 15-(b) exhibit a clear river pattern.
According to the cleavage fracture morphology of the fracture surface, it can be determined that the cracked material experienced a brittle fracture. Because the brittle fracture surface was smooth and had no plastic deformation, the sample had a favorable assembly, which meets the requirements of fracture splitting processing.

In summary, the brittle fracture characteristics of the fracture zone meets the requirements of fracture splitting processing; the brittle fracture properties of the fracture zone can enable the fracture material to be cracked smoothly.

4 Conclusion

1. The thickness of T10A in the test should be between 2 mm and 3 mm, so that 0.25wt%C cast carbon steel and T10A can be fully combined in the interface, and the brittle material is sufficiently thick for splitting.

2. Investment casting of a bimetallic connecting rod is reasonable. The calcining temperature of the sand mold should be 1200°C; the preheating temperature of T10A should be 500°C; the casting temperature of the 0.25wt%C cast carbon steel should be 1600°C; the sample should be insulated for 20 minutes, and then air-cooled. And the thickness of T10A is controlled at 2-3 mm. The bimetallic sample should have a favorable bonding interface, with no cracks, holes, or other defects. These experiments can construct a favorable foundation for subsequent experiments in forging and heat treatment.

3. The experimental results proved that the appearance of the fracture zone is a cleavage fracture and is flat, with no plastic deformation, which facilitates the meshing of the cracked surface when the specimen is assembled. Therefore, the brittle fracture characteristics of the fracture zone and the ductile fracture characteristics of the main zone can meet the requirements of a connecting rod made by fracture splitting.

4. The experimental results show that the bimetallic samples satisfy the splitting and
mechanical requirements of the connecting rods made by fracture splitting, and the coupling performance is favorable. This technology can enlarge the choice of materials and improve the quality of fracture splitting.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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References


# Tables

**Table 1** Chemical compositions of 0.25wt%C cast carbon steel and T10A (mass fraction, %)

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<th>material</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Cr</th>
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<td>0.25wt%C cast carbon steel</td>
<td>0.22-0.29</td>
<td>0.17-0.37</td>
<td>0.50-0.80</td>
<td>≤0.035</td>
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<td>T10A</td>
<td>0.95—1.04</td>
<td>≤0.35</td>
<td>≤0.40</td>
<td>≤0.020</td>
<td>≤0.030</td>
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Table 2 Some pivotal process parameters

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<td>Thickness of T10A</td>
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<tr>
<td>Temperature of dewaxing treatment</td>
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<td>Temperature of calcining</td>
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<td>Temperature of preheating</td>
<td>500 °C</td>
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<td>Temperature of casting</td>
<td>1600 °C</td>
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<td>Time of insulation</td>
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FIGURES CAPTIONS

Fig. 1 The system of the side injection casting

Fig. 2 The mold shell of the side injection type

Fig. 3 The casting defects distribution of the connecting rod

Fig. 4 Relationship between the lowest temperature and time of the cracked material

Fig. 5 Relationship between the lowest temperature and time of the cracked material under different volume ratios

Fig. 6 Bimetallic casting billet

Fig. 7 Bimetallic casting sample

Fig. 8 The carbon element diffuses at the bimetallic interface

Fig. 9 Microstructure images of the bimetallic interface. a) Microstructure of carbon steel; b) Microstructure of the transition zone; c) Microstructure of T10A;

Fig. 10 The bimetallic sample broke in the carbon steel region after stretching

Fig. 11 Hardness distribution of the bimetallic interface

Fig. 12 Dimension figure of sample. a) Tensile test sample; b) Test sample with V type cleavage groove;

Fig. 13 Reassembled samples under non-loading and loading force. a) Reassembled sample without load; b) Reassembled sample with load;

Fig. 14 Macroscopic fracture of the cracking zone
Fig. 15 Microstructure fracture of the cracking zone. a) Microstructure of the fracture zone; b) Enlargement of the red-framed part;
Fig. 1 The system of the side injection casting
127x107mm (85 x 84 DPI)
Fig. 2 The mold shell of the side injection type

187x177mm (200 x 200 DPI)
Fig. 3 The casting defects distribution of the connecting rod

192x176mm (72 x 72 DPI)
Fig. 4 Relationship between the lowest temperature and time of the cracked material

Solidus temperature of T10A
Fig. 5 Relationship between the lowest temperature and time of the cracked material under different volume ratios
Fig. 6 Bimetallic casting billet

108x59mm (92 x 92 DPI)
Fig. 7 Bimetallic casting sample

0.25wt% C cast carbon steel
(body material)

T10A
(fracture splitting material)
Fig. 8 The carbon element diffuses at the bimetallic interface
Fig. 9 Microstructure images of the bimetallic interface. a) Microstructure of carbon steel; b) Microstructure of the transition zone; c) Microstructure of T10A;

237x179mm (289 x 288 DPI)
Fig. 10 The bimetallic sample broke in the carbon steel region after stretching.
Fig. 11 Hardness distribution of the bimetallic interface

0.25wt% C cast carbon steel

T10A

Interface

200 210 220 230 240 250 260

2 1 0 -1 -2 -3

distance (mm)

hardness (HV)

184x137mm (72 x 72 DPI)
Fig. 12 Dimension figure of sample. a) Tensile test sample; b) Test sample with V type cleavage groove;

245x112mm (72 x 72 DPI)
Fig. 13 Reassembled samples under non-loading and loading force. a) Reassembled sample without load; b) Reassembled sample with load;
Fig. 14 Macroscopic fracture of the cracking zone

244x90mm (113 x 113 DPI)
Fig. 15 Microstructure fracture of the cracking zone. a) Microstructure of the fracture zone; b) Enlargement of the red-framed part;

240x89mm (115 x 115 DPI)