Comparative analysis of the fracture splitting deformation of the big end for C70S6, 36MnVS4 and 46MnVS5 connecting rods

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Abstract. During the fracture splitting process of the connecting rod, the plastic deformation, especially the plastic deformation before cracking, not only causes the big end hole of the connecting rod to be out of roundness, but also increases the residual stress, affecting the assembly precision and even the service life of the connecting rod. In this paper, the mechanical properties of microalloyed steel C70S6, 36MnVS4 and 46MnVS5 connecting rod were determined by tensile test. The displacement field, plastic strain and the deformation principle of the big end before the crack initiation of the fracture splitting of the connecting rod were numerically simulated. The results show that the yield strength, tensile strength and plasticity index of the new medium carbon microalloyed steels 46MnVS5 and 36MnVS4 are significantly higher than those of C70S6. However, the C70S6 connecting rod has a long loading time before crack initiation, and the plastic deformation area of the groove root front is large and the strain is high. The plastic deformation of 36MnVS4 and 46MnVS5 connecting rods is small and the area is concentrated. Among the three, the 46MnVS5 connecting rod has the smallest deformation and the C70S6 connecting rod has the largest deformation.

1. Introduction
Fracture splitting has become the main way for the machining of connecting rod. The three key processes of connecting rod machining include prefabricated incision, directional crack and bolt assembly [1], among which directional splitting has the largest impact on the deformation of the big end of connecting rod. The roundness loss of the big end hole is one of the important detected items for the machining of connecting rod. The large deformation not only causes the roundness loss of the big end hole, but also reduces the assembly accuracy and even affects the performance of the connecting rod.

C70S6 is the first mature case of micro-alloy non-quenched and tempered steel for the fracture splitting of connecting rod [2], which is characterized with good purity and excellent splitting performance [3,4]. However, its low yield strength, poor cutting performance and unsatisfactory fatigue strength make it difficult to achieve the design for structural weight reduction [5, 6]. In order to adapt to the lightweight development of automobiles, new connecting rod materials of 36MnVS4, 38MnV5 and 46MnVS5 have been developed in recent years [7]. Their comprehensive mechanical properties...
have been significantly improved compared with C70S6 connecting rod, and the fatigue strength can be increased by about 10%, which has a great potential of development and application.

In view of the transient nature and the complexity of the dynamic fracture splitting process, it is difficult to dynamically capture the parameters. In this paper, the numerical fracture splitting simulation analysis of three typical microalloyed non-quenched and tempered connecting rods of C70S6, 36MnVS4 and 46MnVS5 is carried out. The mechanical properties of the three materials were obtained by the tensile strength test of the forged sample, and the fracture splitting deformation of the big end of the connecting rods were numerically analyzed.

2. Material properties

The chemical compositions of C70S6, 36MnVS4 and 46MnVS5 microalloyed non-quenched and tempered steels are shown in Table 1. It can be seen that compared with C70S6, the carbon contents of 36MnVS4 and 46MnVS5 are significantly reduced, the content of S, Mn, Cr, V increases; The reduction of C is conducive to improving machinability and toughness. The increase of the content of the above alloy elements can make grain refined and get higher strength, enhance the toughness of materials, and make up for the influence of the reduction of C on mechanical properties. The reduction of S and the increase of Mn can improve the thermal processability of materials.

| Material   | C  | Mn  | Si  | S   | Cr  |
|------------|----|-----|-----|-----|-----|
| C70S6      | 0.71 | 0.50 | 0.20 | 0.07 | 0.12 |
| 36MnVS4    | 0.36 | 0.99 | 0.70 | 0.05 | 0.25 |
| 46MnVS5    | 0.47 | 1.10 | 0.75 | 0.06 | 0.30 |

The forging of the connecting rod is carried out at 1150~1250 °C, and the air-controlled cooling is processed after forging according to the CCT curve of the three materials (first rapid air cooling and heap of cooling) to obtain good pearlite and ferrite structure, suitable hardness and mechanical properties. The forging rod of the connecting rod was sampled to prepare a sample with a diameter of φ 5 mm and a length of 25 mm. The mechanical properties obtained by the tensile test are shown in Table 2.

| Material   | Samples | Yield Strength(σs)/MPa | Tensile Strength(σb)/MPa | rate of reduction/% | Elongation/% |
|------------|---------|------------------------|--------------------------|-------------------|-------------|
| C70S6      | 1#      | 605                    | 990                      | 25.5              | 14.0        |
|            | 2#      | 590                    | 985                      | 28.0              | 16.5        |
|            | 3#      | 585                    | 980                      | 25.0              | 17.5        |
|            | average | 593                    | 985                      | 26.2              | 16          |
| 36MnVS4    | 1#      | 895                    | 1100                     | 36.0              | 22.0        |
|            | 2#      | 920                    | 1130                     | 42.0              | 23.0        |
|            | 3#      | 895                    | 1130                     | 39.0              | 19.5        |
|            | average | 903                    | 1120                     | 39                | 21.5        |
| 46MnVS5    | 1#      | 795                    | 1130                     | 29.5              | 18.5        |
|            | 2#      | 775                    | 1110                     | 33.0              | 16.5        |
|            | 3#      | 830                    | 1120                     | 29.5              | 18.0        |
|            | average | 800                    | 1120                     | 30.7              | 17.7        |

It can be seen that the high carbon microalloyed steel C70S6 connecting rod has the lowest yield and tensile strength, the lowest rate of reduction and elongation, the 36MnVS4 connecting rod is the highest, and the 46MnVS5 is in the middle. The yield ratio of C70S6 is only 0.602, which is significantly lower than that of medium carbon microalloyed steel.
3. Numerical analysis model construction

3.1. Principle of fracture splitting mechanics of connecting rod

The fracture splitting process of the connecting rod is shown in Figure 1. The wedge-shaped pull rod moves downward. The wedge-shaped surface of the pull rod pushes the horizontal movement of the moving sleeve to continuously apply tensile load to the large hole of the connecting rod. Stress concentration occurs at the root of the large hole of the connecting rod, and the slit is cracked. And the crack spreads rapidly until the fracture is separated into the connecting rod body and the connecting rod cover.

The fracture splitting essence of the connecting rod is the I-type quasi-brittle fracture of the elastoplastic material after a small yield. The theoretical basis is that the external stress is perpendicular to the fracture surface, and the low stress brittle fracture is easy to occur, the plastic deformation is small and the fracture is flat. And the maximum tensile stress is adopted as the basic criterion in the finite element numerical simulation [8].

![Figure 1. Fracture splitting diagram of the connecting rod](image1.jpg)

3.2. Parameters of connecting rod and groove root

One connecting rod of a car engine is selected, the main dimensions are shown in Figure 2(a). The diameter of the big end hole is 41.80 mm, the center distance between the big end hole and small end hole is 147.50 mm, the bolt hole diameter is 6.50 mm, and the distance between the bolt holes and the outer edge is 2.10 mm. The thickness of the connecting rod is 17.90 mm.

According to the previous research experience on the fracture splitting of C70S6 connecting rod, 0.4-0.6 mm for the groove depth, 0.1-0.3 mm for the radius of curvature are chosen. To prevent the influence of different geometric parameters on the modeling results, the groove root selects the same parameters. The size of the groove root was as Figure 2(b): the groove length L=17.9 mm, the groove depth h=0.5 mm, the opening angle=60°, and the radius of curvature = 0.2 mm.

![Figure 2. Parameters of the connecting rod and the groove root](image2.jpg)
3.3. Geometric modeling
The geometry, constraint and force of the connecting rod are symmetrical about the mid-surface and the central axis, while the connecting rod small end, the connecting rod, the boss on the connecting rod, the outer round corner have little influence on the fracture splitting process, and thus the structure such as the small end and the rod are neglected.

Based on the geometry of the connecting rod and the symmetry of the restraint force, and in order to improve the calculation efficiency and reduce the difficulty of meshing, the quarter end of the connecting rod is modeled, and the moving and fixed block are simplified to one quarter. The model is shown as Figure 3. The simplified model has a plane of symmetry along the thickness direction (middle plane, plane of symmetry 1) and a plane of symmetry along the central axis (symmetric plane 2).

3.4. Boundary conditions and load handling
The model is simplified to 1/4, which has two symmetry planes. The displacement Uz=0 and Ux=0 are applied on the nodes in the symmetry plane 1 (thickness midplane) and the symmetry plane 2 as shown in figure 3.

There are two contact pairs in the model, which are the contact between the big end and the fixed sleeve and the big end and the movable sleeve. A fully fixed constraint is applied to the fixed sleeve, which limits all rotations and Uz = Ux = 0. The speed load is applied to the moving sleeve along the X direction of the connecting rod.

4. Numerical simulation results and analysis
4.1. Displacement field before crack initiation
The displacement of the big end before the cracking of the connecting rod is shown in Figure 4, where U1 stands for the displacement in the X direction (the direction of the connecting rod axis), U2 stands for the displacement in the Y direction (the direction of the vertical axis and parallel to the predetermined fracture surface), and U3 stands for the displacement in the Z direction (the thickness direction), U stands for the total displacement.

Table 3 shows the maximum displacement of the big end of the connecting rod in three directions. It can be seen that the displacement of the big end of the C70S6 connecting rod in three directions and the total displacement are all the largest, 36MnVS5 is the second, and 46MnVS5 is the smallest. Since the tensile stress is applied to the fixed sleeve and the movable sleeve in the direction of the axis X in the big end of the connecting rod, the big end of the connecting rod exhibits an elongation in the X direction and the maximum displacement in the X direction occurs in the inner wall of big end; The largest displacement in the Y direction occurs near the groove root and the predetermined fracture surface, and produces a Y-direction compression deformation; the displacement in the Z direction is small during the fracture splitting of the connecting rod. This indicates that the fracture splitting of the big end mainly shows the appearance of out of roundness in the X-Y direction, in which the C70S6 ellipse is the most obvious, and 36MnVS5 and 46MnVS5 are sequentially decreased.
Figure 4. Displacement of the big end before crack starts

Table 3. Displacement change of the big end of the connecting rod

| Material | C70S6         | 36MnVS4       | 46MnVS5       |
|----------|---------------|---------------|---------------|
| U1,Magnitude | 0.032672      | 0.021365      | 0.013746      |
| U2,Magnitude | 0.003554      | 0.001602      | 0.000617      |
| U3,Magnitude | 0.000459      | 0.000251      | 0.000106      |
| U,Magnitude  | 0.032672      | 0.021365      | 0.013746      |

4.2. The deformation of the big end

Figure 5 and Figure 6 respectively show the maximum, minimum and intermediate displacement of the connecting rod of the three materials in the X and Y directions with the increase of time. The x-direction displacement is the largest at the contact point between the moving sleeve and the inner wall of the big hole along the axis of the connecting rod, and the X-axis displacement is the smallest. According to Figure 4, the maximum displacement in the Y direction is located in the groove root and the predetermined fracture surface region, and the minimum displacement in the Y direction is in the region of 20 to 30 degrees from the X-axis and Y-axis.
Figure 5. Change of X-direction displacement of big end with time

Figure 6. Change of Y-direction displacement of big end of connecting rod with time

It can be seen from Figure 5 that the x-direction displacement of the big end of the connecting rod of the three materials changes in the same pattern with time. The maximum displacement increases linearly with the increase of time, and the minimum displacement is always 0. It indicates that with the increase of time, the displacement of each point in the big end along the X direction varies unevenly.

It can be seen from Figure 6 that the Y-direction displacement of the connecting rod of the three materials changes with time basically in the same rule. The maximum displacement and minimum displacement increase with time, and the intermediate displacement changes little. The displacement of the big end of the connecting rod in Y direction is uneven.

4.3 Plastic strain near the groove root

Figure 7 shows the plastic strain of connecting rod before cracking. It can be seen that the plastic deformation of connecting rod is completely concentrated near the groove root, and the plastic strain of other areas is 0, which further indicates that the fracture splitting of connecting rod is a quasi-brittle fracture with yield within a small range near the groove root. As shown in Figure 4, the big end of the connecting rod extends in the X direction and contracts in the Y direction in the predetermined fracture surface area. After unloading, a large amount of elastic deformation can be released, and the big end only retains a small amount of ellipticity, which can be completely eliminated by subsequent fine boring.

Figure 7. Plastic strain near groove root
According to Figure 7, the plastic deformation of connecting rod C70S6 is the largest, 36MnVS4 is in the middle, and 46MnVS5 is the smallest. C70S6 connecting rod has the longest loading time before cracking. And due to the low yield strength of connecting rod C70S6, the plastic deformation zone of the front of the groove root is large and the peak of plastic strain is high. However, the yield ratios of 36MnVS4 and 46MnVS5 are high, the crack loading time of the connecting rod is short, the plastic deformation zone is small, and the peak of plastic strain is low (especially the latter), indicating that the incision sensitivity of the two is higher. Large deformation of C70S6 connecting rod may lead to large residual stress, so it is necessary to pay attention to the optimization of incision parameters, splitting fixture design and reasonable selection of force and energy parameters to avoid the impact on the assembly accuracy.

5. Conclusion
(1) After forging and air-controlled cooling, the yield strength and tensile strength of the medium carbon microalloyed steels 36MnVS4 and 46MnVS5 are significantly higher than those of C70S6. And with the decrease of the carbon content, the plasticity index increases.
(2) Before the crack of the connecting rod, the big end of the connecting rod is elongated in the direction of the axis of the connecting rod and contracts in the direction parallel to the predetermined fracture surface, so that the circle in the XY direction is lost; and the deformation amount increases as the loading time increases; The ovality of C70S6 connecting rod is the most obvious, 46MnVS5 is the lowest. The deformation of the connecting rod in the thickness direction is extremely small.
(3) The loading time of C70S6 connecting rod is the longest before cracking, the plastic deformation zone of the front of the groove root is the largest, and the peak of the plastic strain is the highest; while the 36MnVS4, 46MnVS5 connecting rod has a high yield ratio, the loading time of the connecting rod is short before cracking, and the plastic deformation area is small. And the plastic strain of the 46MnVS5 connecting rod significantly decreases.

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