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In situ monitoring the properties of 20 carbon steel and ductile iron under combined tension and three-point bending loadings

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ABSTRACT

This paper is concerned with the bending strength of the materials that is improved under the combined tension and three-point bending loadings. During the tension and three-point bending process, the whole evolution of metallographic structures of the specimens is *in situ* monitored by the microscope of *in situ* monitoring module. Moreover, a finite element analysis (FEA) model is established by using ABAQUS to analyze the distribution of stress, when the pre-tensile stress is different, but the deflection of the three-point bending is same, 3.0 mm. The simulation results are consistent with the experiment results. Therefore, it is clearly that the bending strength is increased with the increase of pre-tensile stress, when the bending load is 1750N every time. And the yield point of material is obviously disappeared under combined tension and three-point bending loadings. Meanwhile, the *in situ* metallographic images verify from the microscopic point of prospective that the bending strength of the material has been improved.

1. Introduction

In practical engineering applications, the materials are usually subjected to combined tension and three-point bending loadings at the same time. Therefore, the failure mechanism of the material under combined tension and three-point bending loadings should be examined deeply to promote practical application. The combined tension and bending is proposed by Benedyk et al. [1] to investigate material properties at high levels of straining. In recent years, many scholars have made a great deal of interests in studying the materials' properties under combined tension and bending loadings. He et al. [2] studied the forming limits of a sheet metal under continuous-bending-tension loading. Li et al. [3] investigated a global limit load solution for plates with embedded off-set elliptical cracks under combined tension and bending. Lei and Budden [4] solved the global limit load solutions for plates with surface cracks under combined biaxial forces and cross-thickness bending. Zerbst et al. [5] treated the reference loads for plates with semi-elliptical surface cracks subjected to tension and bending for application within R6 type flaw assessment. Wilding et al. [6] introduced a planar compliant joints design in lamina emergent mechanisms under combined bending and axial loading conditions.

Furthermore, Khoshbakht et al. [7] researched on the failure of woven composites under combined tension-bending loading. The localization and failure in aluminum shells due to crushing induced bending and tension was presented by Giagmouris et al. [8]. Moreover, Chatterjee et al. [9] studied the grain-level deformation and residual stresses in Ti-7Al under combined bending and tension using high energy diffraction microscopy. Chu et al. [10] solved the two-dimensional elasticity solution of elastic strips and beams made of functionally graded materials under tension and bending. Behavior of $[0]_8$ woven composites under combined bending and tension loading was handled by Khashaba et al. [11]. Nonlinear tension-bending deformation of a shape memory alloy rod was carried out by Shang and Wang [12].

Others, Orakdöğen et al. [13] established a finite element analysis (FEA) of functionally graded plates for coupling effect of extension and bending. In order to analyze the load-bearing capacity and damage of double scarf adhesive joints under combined loading of tension and bending, a finite element model was applied by Liao et al. [14]. A finite element analysis model was developed to

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conduct mechanism analysis and parametric analysis of the composite members under combined tension and bending that was investigated by Wang et al. [15]. A numerical simulation of the continuous bending under tension test is analyzed by Hadoush et al. [16].

Although a large number of papers on the theoretical, FEA and experiment of combined tension and bending have been published in the past several decades, study on the *in situ* microscopic metallographic morphology by using the microscope is rare. Therefore, the aim of this paper is to *in situ* monitoring the microscopic metallographic morphology changing of the material under combined tension and three-point bending loadings. At the same time, a FEA model is established to simulate the stress distribution on the specimen under the combined tension and three-point bending loadings.

In the experiment, the ductile materials, 20 carbon steel and brittle materials, ductile iron, are used to test under the combined tension and three-point bending loadings. The 20 carbon steel has good toughness, plasticity and welding performance, is widely used in automobiles, tractors, steam turbines, boilers and railway related parts of the production and manufacture [17–19]. And ductile iron with high strength, medium toughness and plasticity, high overall performance, good wear resistance and vibration damping, mainly served in the manufacture of a variety of power machinery crankshaft, camshaft, connecting shaft, connecting rod, gears, clutch plates, hydraulic cylinder and other parts [20–23]. The bending strength of material is improved under the combined tension and three-point bending loadings. With the same bending deflection, the bending strength is increased with the pre-tensile stress rising. The FEA result is in accordance with the experiment result. Through the analysis of the *in situ* metallographic images of the material, it can be verified from the microscopic point of view that the pre-tensile load and the holding load can improve the bending strength of the material.

2. Experiment

2.1. Specimens preparation

In this experiment, the specimens are made of 20 carbon steel and ductile iron. The chemical composition of the 20 carbon steel and ductile iron is given in Tables 1 and 2. The specimen is round bar and its dimension is shown in Fig. 1.

During the experiment, the specimen is served under the combined tension and three-point bending loadings. The tension is applied in the *X* axis, and three-point bending is used in the *Y* axis. The span (*L*) of three-point bending supports is 96.0 mm. The diameter of specimen between the supports is 6.0 mm. In order to *in situ* observe the deformation of specimen during the combined tension and three-point bending loadings, a 10.0 mm (*L*) $\times$ 2.0 mm (*W*) plane is cut out from the surface of round bar, which leis in the middle of the specimen. Before the experiment, the specimens are ground with waterproof emery paper from 500-grit to 7000-grit manually. And then, the specimens are corroded by the 5% nitric acid alcohol solution for about 50 s (20 carbon steel) and 26 s (ductile iron). Finally, the specimens are rinsed by the 99% alcohol and blown dry.

Table 1
Chemical compositions of the 20 carbon steel (in wt %).

C	Si	Mn	S	P	Cr	Ni	Cu	Fe
0.2	0.22	0.46	0.15	0.23	0.24	0.2	0.2	rest

Table 2
Chemical compositions of the ductile iron (in wt %).

C	Si	Mn	S	P	Mg	Fe
3.6	2.6	0.45	0.05	0.06	0.04	rest

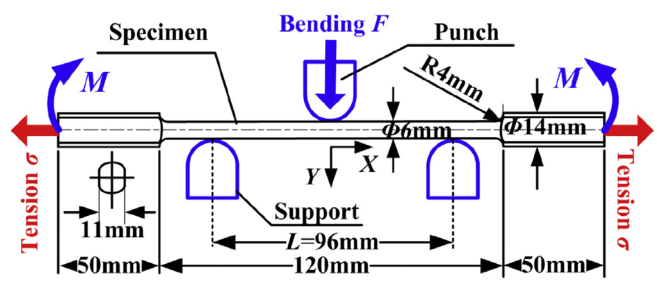

Fig. 1. The dimension of specimen and it is tested by the combined tension and three-point bending loadings.

2.2. Combined tension and three-point bending loadings test

The combined tension and three-point bending loadings test system is consisted of tension test module, three-point bending test module and *in situ* monitoring module (OLYMPUS LG-PS2 microscope) as shown in Fig. 2. The combined tension and three-point bending loadings tester is designed by ourselves that is calibrated by “INSTRON”. In the three-point bending test module, the distance of supports is 64.0 mm, the radius of punch and support is 5.0 mm.

Before the experiment, first, adjusting the distance between the upper and lower jigs, makes the specimen just clamping. At the same time, the punch of three-point bending must be point to the center of the specimen (The position of the small plane lies on the

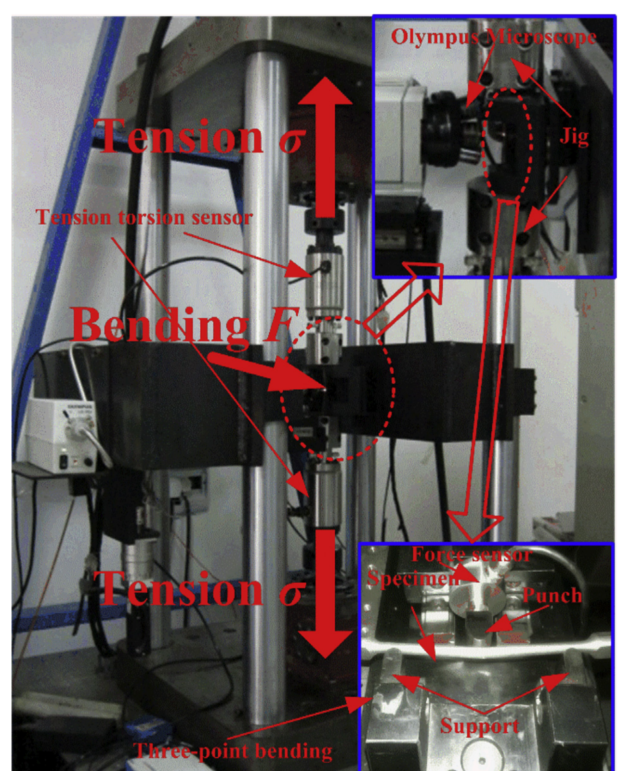

Fig. 2. The experiment system of combined tension and three-point bending loadings.