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Tensile fracture behavior of Ni- and Cr–C/Ni-coated high-carbon tool steel (AISI 1090)

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HIGHLIGHTS

- Tensile behavior of uncoated, Ni-, and Cr–C/Ni-coated AISI 1090 was studied.
- EP of steel decreases significantly after coating a 5-µm-thick Cr–C deposit.
- Cracking facets and cracks were found in the middle of Cr–C/Ni-coated specimens.
- Cracking facets were formed in the fracture surface through branch cracking.

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ABSTRACT

The tensile fracture behavior of Ni- and Cr–C/Ni-coated high-carbon tool steel specimens was studied. The Cr–C coating was prepared in a Cr^{3+}-based plating bath, and the Ni coating was prepared in a Ni-sulfate bath. The experimental results indicate that the yield and ultimate tensile strengths were not changed after Ni- or Cr–C/Ni-coating. However, the elongation percentage of the steel specimen was clearly reduced after Cr–C/Ni-coating. According to the fractography study, the fracture feature with necking and a cup-and-cone appearance was observed in the steel and Ni-coated steel specimens after the tensile test. However, the fracture feature of the Cr–C/Ni-coated steel specimens with relatively low elongation percentages exhibited an obvious cracking plateau. Under the application of tensile stress, cracks in the Cr–C coating propagated through the Ni coating and then into the steel substrate, forming a cracking plateau and, decreasing its elongation percentage. Moreover, branch cracking was observed during crack propagation to develop a fracture appearance with some cracks and crack facets.

1. Introduction

High-carbon tool steel is widely used as a material for fine and precision mechanical parts because of its high heat-treatable hardness, suitable mechanical properties and low cost. However, the corrosion resistance of high-carbon tool steel is poor to meet the requirement of industrial applications. Generally, Zn, Ni, Cr and their alloy coatings are used to improve the corrosion resistance of steel substrates [1–5]. Ni, Cr and their alloy coatings are commonly used for applications in precision mechanical parts, because the coatings have suitable mechanical properties and a fine-looking appearance. However, the tensile behavior of Ni-, Cr–C/Ni-coated steel specimens is rarely reported.

Applications of a material, and its mechanical properties, such as the yield, ultimate tensile strengths, Young's modulus and elongation percentage, must be evaluated for appropriate design. To evaluate the mechanical properties of a specimen, tensile test is widely used. Many researchers have shown that the tensile behavior of a steel specimen can greatly change after different heat treatments or alloying with small amounts of elements [6–8]. Because the increase in the cross section of a tensile specimen is so small after coating with a thickness of a few micrometers, it can be reasonably assumed that the tensile behavior of a steel specimen is not affected or slightly affected after thin film coating. In our previous study on the tensile fracture behavior of Cu- and Ni/Cu-coated Mg alloy [9], we observed that the tensile cracking of Mg alloy is obviously affected after coating with a Cu deposit with a

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thickness of a few micrometers. An obvious decrease in the elongation percentage of the Mg alloy was observed after coating with a thin Cu deposit.

In this study, the tensile fracture behavior of uncoated, Ni- and Cr–C/Ni coated high carbon tool steel specimen (AISI 1090) was investigated. The Ni coating was prepared in a Ni-sulfate bath, and the Cr–C coating was prepared from a Cr^{3+}-based electroplating bath, which is an eco-friendly process in applications.

2. Experimental procedure

Commercial bar-type high-carbon tool steel (AISI 1090) was shaped into tensile specimens with a gauge diameter of 4 mm and a gauge length of 14 mm, as shown in Fig. 1. The chemical composition of the steel specimen is listed in Table 1. The as-received steel specimen was spheroidization-annealed to develop spherical Fe_3C particles in the α-Fe substrate to achieve suitable forming and machining ability. Electroplating of the steel specimen was performed in a rotating cylinder cell (AMETEK Model 616A), in which the steel tensile specimen and a platinised Ti mesh were used as the working and counter electrodes, respectively. Before electroplating, the surface of the steel tensile specimen was mechanically ground with 1200-grit emery paper, cleaned in deionised water, and dried with an air blaster.

Two types of coatings, a Ni coating and a Cr–C on Ni coating, denoted as Cr–C/Ni coating, were electroplated on the steel tensile specimens. The Ni coating was prepared at 50 °C in a Ni-sulfate bath composed of 300 gL^{-1} $NiSO_4$, 50 gL^{-1} $NiCl_4$, 20 gL^{-1} H_3BO_3, and 3 gL^{-1} SDS. Some of the Ni-coated steel specimens were further electroplated with Cr–C coating in an eco-friendly Cr^{3+}-based bath. The Cr–C deposits were prepared in an electroplating bath containing 0.8 M $CrCl_3 \cdot 6H_2O$ as the main metal salt, urea as a complexing agent and a small amount of buffer salts with a pH value of 1.1 [10,11]. Therefore, three types of tensile specimens, including uncoated, Ni-, and Cr–C/Ni-coated steel specimens, were prepared for the tensile test in this study.

Fig. 2 (a)-(c) show uncoated, Ni- and Cr–C/Ni-coated steel specimens for the tensile test, respectively. As observed in Fig. 2(b) and (c), the gauge length, upper and lower taper regions of the coated steel tensile specimens were uniformly electroplated without any visual defects to ensure the occurrence of tensile fracture in the gauge length. The tensile behavior of a coated steel tensile specimen was evaluated with at least five specimens under the same electroplating condition. The stress-strain relation of a tensile specimen was determined when the stress-strain curves of at least three tested specimens were identical and repeatable.

The tensile behavior of an uncoated or a coated steel specimen was tested with a servo-hydraulic closed-loop material testing system (MTS 810) with a constant strain rate of 1.2×10^{-3} s^{-1} under controlled displacement at room temperature. After the tensile test, the tensile specimens were fractographically examined using an optical microscope (OM, Olympus BH2-UMA, Olympus Ltd., Tokyo, Japan) and a scanning electron microscope (SEM, Hitachi S-3000N, Hitachi Ltd., Tokyo, Japan) equipped with an energy-dispersive X-ray spectrometer (EDS) for chemical composition analysis. The chemical composition of Cr–C deposit was quantitatively analyzed with an electron probe X-Ray microanalyzer, (EPMA, JEOL JXA-8200, Japan Electron Optics Laboratory Co., Ltd., Tokyo, Japan) with an accelerating voltage of 15 kV and a beam current of 50 nA. The Cr and C contents in the Cr–C deposit is shown in Table 2, in which 95.9 wt.% Cr and 4.1 wt.% C were detected. This result is fully in agreement with many researches in which about 2–9 wt.% C could be found in the Cr–C deposit prepared in a Cr^{3+}-based plating bath [12–14].

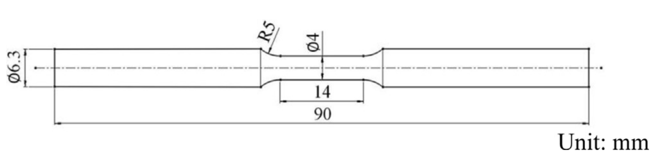

Fig. 1. Dimensions of the tensile specimen used in this study.

Table 1
Chemical composition of the AISI 1090 specimen used in this study.

Element	C	Si	Mn	S	P
wt.%	0.92	0.35	≦0.50	≦0.03	≦0.03

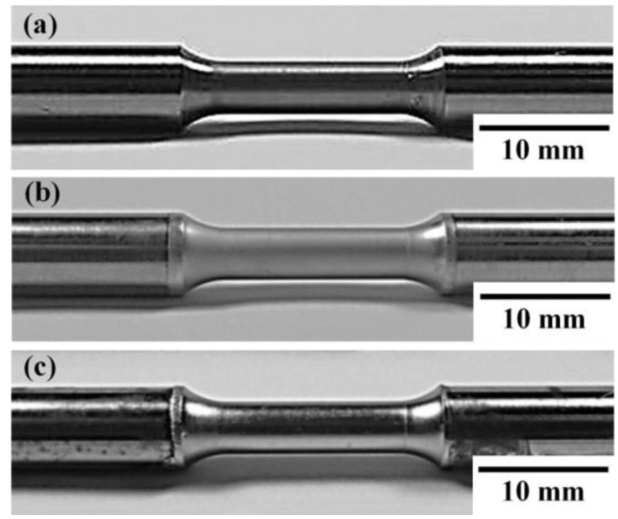

Fig. 2. (a) Uncoated, (b) Ni-, and (c) Cr–C/Ni-coated steel tensile specimens.

3. Results and discussion

3.1. Tensile test

The tensile behavior of the uncoated, Ni- and Cr–C/Ni-coated steel specimens is shown in Fig. 3. In this tensile test, the thickness of the Ni coating was 10 μm and that of the Cr–C coating was 5 μm. The ultimate tensile strength (UTS) and elongation percentage (EP) of the uncoated or coated steel specimen can be evaluated from its engineering stress vs. engineering strain relation. As observed in Fig. 3, the uncoated and coated steel specimens have almost the same UTS of approximately 880 MPa. The EP of the steel specimen is 18.5%; however, this value decreased to 17.7% after the Ni coating and then to 12.3% after the Cr–C/Ni coating, which indicates that the EP of the steel specimen clearly decreased after the Cr–C/Ni coating.

The stress-strain curves of the Ni-coated steel specimens with Ni-coating thickness values of 3, 10 and 20 μm are shown in Fig. 4. The tensile behavior of the Ni-coated steel specimens is almost

Table 2
Chemical composition of the Cr–C deposit prepared in this study.

Element	Cr	C
wt.%	95.9	4.1