Hot stamping of ultra-thin ferritic stainless steel for microchannels

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The ferritic stainless steel is one of the potential materials for manufacturing bipolar plates with good corrosion resistance and low cost. However, due to its poor formability at room temperature, cold stamping process is insufficient to form microchannels. In this work, the mechanical properties of ultra-thin ferritic stainless steel 446 are investigated via high-temperature uniaxial tensile tests. Results show that the strength of ferritic stainless steel 446 at 800 °C decreases significantly and the elongation increased by approximately 114% compared with that at room temperature. Hence, hot stamping experiment is conducted at 800 °C to verify the feasibility of the hot stamping process for ferritic stainless steel microchannels. Ultimately, the hot stamping process is capable of forming microchannels at 800 °C.

Keywords: Ferritic stainless steel; Hot stamping; Microchannel; Formability.

1. Introduction

The proton exchange membrane fuel cells (PEMFC) are widely utilized in transportation, aerospace, etc. [1, 2]. Bipolar plates (BPPs) with fine microchannel features are the key components in a PEMFC stack. With the advantage of good corrosion resistance and low cost [3], ferritic stainless steel (FSS) is receiving increasing attention in manufacturing BPPs. However, the poor formability of ultra-thin FSS at room temperature impedes the fabrication of fine microchannel structures, restricting the improvement of power density of PEMFC. Based on the fact that increasing forming temperature can effectively reduce the strength of metal materials and enhance their plasticity [4], many scholars have carried out warm/hot stamping process of BPPs. Guo et al. [5] proposed a hot stamping process of ultra-thin SS316L bipolar plates, improving the dimensional accuracy and uniformity of microchannels. Zhang et al. [6] observed that ultra-thin titanium sheets exhibit significantly higher fracture limits at 700 °C compared with room temperature. Then they performed hot stamping process for ultra-thin titanium sheets and ultimately formed a crack-free titanium bipolar plate that was difficult to form through cold stamping.

In this study, high-temperature tensile tests were firstly performed to investigate the ultimate tensile strength (UTS) and the total elongation (TE) of ultra-thin FSS466 at room temperature, 400, 600, and 800 °C. Afterwards, hot stamping at 800 °C for ultra-thin FSS446 microchannels were conducted through a lab-scale hot stamping platform. The features of hot-stamped microchannels including corner radius, wall angle, rib width, channel width and channel depth were measured to compare with design value.

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Furthermore, Cross-section of microchannels formed via hot stamping were observed to assess the uniformity of thickness distribution.

2. Material and experiments

2.1. *Material*

The ultra-thin FSS446 with a thickness of 0.1 mm was employed in this study. Its chemical compositions are listed in Table 1.

Table 1. Chemical composition of the 0.1 mm thick ferritic stainless steel.

Element	Cr	Ni	Mn	Mo	Cu	Co	Nb	Fe	Others
Comp(wt.%)	27.32	1.84	1.88	3.64	0.02	0.02	0.35	66.28	Bal.

2.2. *Uniaxial tensile test*

Uniaxial tensile tests were performed via a high-temperature uniaxial tensile testing system comprising a uniaxial tensile machine, a muffle furnace and digital image correlation (DIC) techniques, as illustrated in Figure 1. The experimental procedure was reported previously in the work of Guo et al. [7]. The geometric dimension of the uniaxial tensile specimen was designed according to the ISO 6892-2 standard, as shown in Figure 2. Three tests were conducted at each temperature to ensure the accuracy of the experimental data.

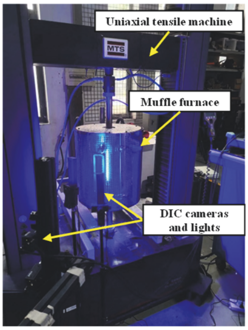

Fig. 1. The high-temperature uniaxial tensile testing system

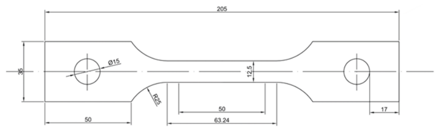

Fig. 2. The geometric dimension of the uniaxial specimen

2.3. *Microchannel hot stamping*

A lab-scale hot stamping platform was built in this study to form ultra-thin FSS446 microchannels at elevated temperature. An on-site resistance heating device including a power source and a pair of electrode clamps was employed to heat the sheet by resistance heating to the target temperature. The platform is illustrated in Figure 3. The microchannel structure is shown in Figure 4a and the cross-section geometry of the stamping die is shown in Figure 4b. At the beginning of hot stamping, the upper die moves downward and the ultra-thin sheet is heated simultaneously. Programming the die closing velocity to ensure that the upper die is exactly 10 mm away from the sheet when the sheet is heated to the target temperature (800 °C). Then the upper and lower die are closed and the hot stamping process is completed.

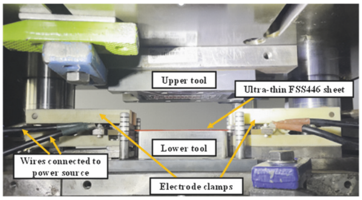

Fig. 3. The hot stamping platform

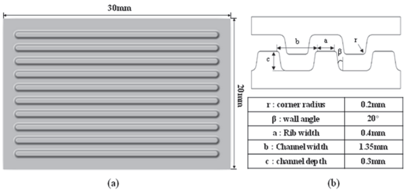

Fig. 4. (a) The design microchannel structure, (b) the cross-section geometry of the stamping tool

2.4. *Geometrical and thickness measurements*

3D surface morphology scanning was conducted to measure the channel depth, rib width and wall angle of the stamped microchannels. Additionally, the thickness distribution was measured on the cross-section of the microchannels by a microscope. The cross-section sample was firstly cut off perpendicular to the channel direction from the stamped part, then was mounted with resin and polished with sandpaper and then observed with an optical microscope to evaluate the thickness of the mircochannels.

3. Results and Discussion

3.1. *Mechanical properties of ultra-thin FSS446*

The engineering stress-strain curves of ultra-thin FSS446 at different temperatures were depicted in Figure 5a. From RT to 600 °C, the stress-strain curves demonstrated that strain hardening is dominant. However, the ultra-thin FSS446 was significantly affected by temperature softening at 800 °C. Variation of UTS and TE of ultra-thin FSS446 with temperature was shown in Figure 5b. It can be observed that the UTS of ultra-thin FSS446 decreases with increasing temperature. The decrease is particularly significant from 600 °C to 800 °C, dropping from 432 MPa to 119 MPa. In comparison to the UTS at RT (616 MPa), ultra-thin FSS446 exhibits significant softening at 800 °C. Moreover, the TE of ultra-thin FSS446 gradually decreases from RT to 600 °C, but shows a significant increase at 800°C from 11.7% to 54%. At 800 °C, ultra-thin FSS446 exhibits the lowest UTS and the highest TE, providing valuable reference for the temperature selection in hot stamping.

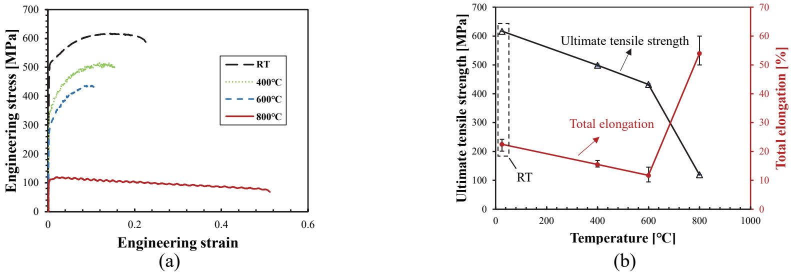

Fig. 5. (a) Engineering stress-strain curves of ultra-thin FSS446 at different temperatures and (b) variation of UTS and ET of ultra-thin FSS446 with temperature

3.2. *Crack-free microchannels stamped at 800 °C*

It is found that the hot stamping process is capable of forming microchannels at 800 °C, while the cold-stamped microchannels are cracked. The cross-sections of microchannels stamped at 800 °C and RT are depicted in Figure 6a. The results indicate that the hot stamping process improves the formability of the ultra-thin FSS446 sheet. The hot-stamped microchannel sample and the 3D surface morphology scanning area are shown in Figure 6b. Measurement results of the microchannel features formed via hot stamping are shown in Table 2. Corner radius, wall angle, rib width, channel width and channel depth are 259.6 μm, 35.4°, 380.0 μm, 1373.3 μm and 346.0 μm, respectively. Those measurements are close to the design values of 200 μm, 35.4°, 400 μm, 1350 μm and 350 μm, which suggests that the dimensional accuracy of hot-stamped microchannels is relatively high. The thickness distribution of the hot-stamped microchannels is shown in Figure 7. The maximum thinning is located at position 4. Overall, the plasticity of FSS446 is improved at high temperatures and the local thinning rate at the corner of the microchannels is decreased. As a result, crack-free microchannels can be formed through hot stamping.

Table 2. Measurement value and design value of the hot-stamped microchannels at 800 °C.

Features	Corner radius [μm]	Wall angle [°]	Rib width [μm]	Channel width [μm]	Channel depth [μm]
Design value	200	20	400	1350	350
Measurement value	251.0 $^{+6.7}_{-7.8}$	35.4 $^{+2.6}_{-1.6}$	380.0 $^{+5.1}_{-4.9}$	1373.3 $^{+5.8}_{-6.2}$	346.0 $^{+1.42}_{-1.37}$

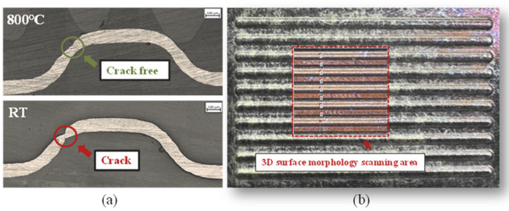

Fig. 6. (a) The cross-section of microchannels under hot and cold stamping processes and (b) the hot stamped microchannel sample

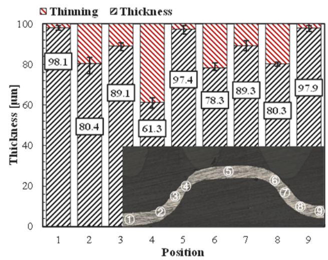

Fig. 7. Thickness distribution of the hot-stamped microchannels at 800 °C.

4. Summary

In this work, the mechanical properties of ultra-thin FSS446 at different temperatures were investigated, and the hot stamping experiment was conducted on the ultra-thin FSS446 microchannels. The main conclusions can be summarized as follow:

(1) Within the testing temperature range, ultra-thin FSS446 exhibits the lowest UTS and the highest TE at 800 °C, measuring 119 MPa and 54%, respectively. Therefore, 800 °C is considered a reasonable temperature for hot stamping of ultra-thin FSS446.

(2) Hot stamping process enhances the formability of ultra-thin FSS446.Therefore, microchannels with a corner radius of 251.0 μm, a wall angle of 35.4°, a rib width of 380.0 μm, a channel width of 1373.3 μm and a channel depth of 346.0 μm can be successfully formed through hot stamping.

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