A study on mechanical properties of ferritic alloy by physical testing for nuclear power fusion reactors

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Abstract. The ferrite plays an important role in key component materials for nuclear power plant. The study was performed on ferritic alloys with various Cr content ranging from 10 to 38wt%. The Vickers-hardness and mechanical test results indicate that the high Cr content will cause a hardening and strengthening effect on the ferrite steel. Meanwhile, it can be concluded that the ferritic alloy suffers a reduction of toughness and a failure mode transition from ductile to brittle fracture with the increasing Cr content from the SEM fractography analysis.

Keywords: Ferrite, iron-chromium alloy, mechanical property, fractography analysis.

1. Introduction
The ferritic alloy with various Cr content is widely used in nuclear power plant due to its advantages of high strength, good corrosion resistance and strong oxidation resistance. As the main pipeline material in the second and third generation nuclear power, Z3CN20.09M duplex stainless steel has sufficient corrosion resistance and reaches a good balance between strength and toughness thanks to a small amount of ferrite [1]. Featured with good strength and excellent oxidation resistance, FeCrAl ferrite steel is regarded as one of the key routes for the development of next generation accident tolerance fuel (ATF) cladding materials [2]. Besides, ferritic-martensitic stainless steel is considered as one of the key structural materials for prospective fourth-generation nuclear power reactors and fusion reactors [3].

The content of chromium element in ferrite has an important influence on the properties of the alloy. In general, the high chromium content in the ferrite may cause serious thermal aging and embrittlement problems during long-term high-temperature service [4, 5], in spite of its positive effect for the strength increase. The local enrichment of Cr caused by spinodal decomposition is the main reason for the performance reduction of CF8 and Z3CN20.09M steels with 20 wt% Cr content, which causes severe toughness reduction and failure risk increase [6-8]. For same reason, the Cr content is also controlled as 13 wt.% in the second-generation ATF FeCrAl cladding, which is much lower than 22 wt.% in the first-generation [9, 10]. Hence, it is important to understand the influence of Cr content on the ferritic alloys properties. The reasonable Cr content determination in ferrite is of great significance for mastering alloy design criteria and improving alloy service performance.

Numerous researches have been conducted on ferritic alloy with various Cr content [4, 5]. However, the present study mainly focuses on its microstructure and spinodal decomposition behaviour. Based on previous study on FeCr binary ferritic alloy, Xiong et al. determined the spinodal line of around 20
wt%Cr at 400℃ by phase field simulation method [5]. The result indicates that the local Cr content tends to fluctuate greatly in the ferritic alloy, which is generally considered as the main cause of performance reduction. Therefore, this phenomenon has been widely studied in micro-scale [11]. However, it is also important to probe the mechanical properties changed by Cr content, which can provide a quantitative analysis on the influencing mechanism of the mechanical properties by Cr enrichment.

In spite of the importance of the Cr content influence, few researches relating the influence of Cr content on the mechanical properties of ferritic alloy has been reported. In this study, four ferritic alloys with various chromium contents were prepared. Then the microstructure characterization and mechanical tests were carried out on the ferritic alloys. Finally, the influence of Cr content on mechanical properties and fracture modes is discussed.

2. Material and experiment methods

A series of four samples of Fe-Cr alloy with various chromium contents from 10 to 38% was prepared by melting 99.99% pure iron and chromium in a vacuum induction furnace. Their chemical analyses are listed in Table 1. For the Fe-10 wt%Cr ferritic alloy sample, homogenization was carried out at 700℃ for 20h, while other samples were homogenized at 1100℃ for 2h and followed by water quenching so as to inhibit the austenite formation and ensure fully ferritic microstructure [12, 13]. The oxide coating on the material was removed for convenience of the subsequent experiments.

Vickers hardness measurement was performed on MHV-50Z instrument with 1 kg load and 10 test results were averaged for each specimen. Room temperature tensile test was conducted on SHIMADZU AG-IC 100KN testing machine with a constant strain rate of 0.00025 s⁻¹. Then, the standard V-notch specimens with dimension of 55mm×10mm×10mm were cut from the samples and subjected to the room temperature instrumented impact test on a Zwick RKP 450 Charpy impact testing machine. The experiment procedure and result analysis followed the ASTM specification [14].

Subsequently, the plate specimens suffered a standard metallographic procedure with final polishing and FeCl₃ etching treatment. The optical observation, scanning electron microscopy (SEM) technique was employed by the ZEISS JG-65 Axio Observer 3 and Tescan VEGA TS 5136 XM scanning electronic microscope.

| Table 1. Chemical analyses of the test alloy (wt %). |
|---------------------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Alloy | Cr   | Mn    | Ni    | Si    | C     | S     | P     | O     | N      |
|-------|------|-------|-------|-------|-------|-------|-------|-------|--------|
| Alloy1 | 9.78 | 0.011 | 0.012 | <0.005 | <0.005 | 0.0096 | <0.005 | 0.022  | 0.0039  |
| Alloy2 | 18.85| 0.0057| 0.010 | 0.0064 | <0.005 | 0.013  | <0.005 | 0.030  | 0.014   |
| Alloy3 | 25.45| <0.005| 0.0096| <0.005 | <0.005 | 0.018  | 0.0056 | 0.050  | 0.018   |
| Alloy4 | 37.61| 0.0060| <0.005| 0.013  | <0.005 | 0.027  | 0.0065 | 0.069  | 0.018   |

3. Results and analysis

3.1. Microstructures and micro-hardness.

Fig. 1 shows the typical microstructure of the binary ferritic alloys with various Cr contents ranging from 10 to 38%. It can be seen that owing to the proper heat treatment, all the homogenized alloys show a similar ferritic microstructure features in spite of different chemical concentrations. It should be note that the ferrite phase is also confirmed by the X-ray diffraction analysis and ferrite content measure by using FERITSCOPE FMP30 of Helmut Fischer GmbH. However, their grain size is apparently different, especially for the Fe-10 wt%Cr alloy.

By using the SEM and Energy Dispersive Spectrometry (EDS) techniques, the morphology and chemical composition of dispersed particles distributed in the matrix was analyzed. Firstly, the Cr content in the matrix was confirmed by EDS, which is in agreement with the result shown in Table 1.
The Cr$_2$O$_3$ oxides and intermetallic phases enriched in C-Si and O-S was found by confirming the similarity in both elemental and morphologic aspect, which frequently appear in ferritic stainless steels [15].

The hardness-composition curve is presented in Fig. 2, it can be seen that the Vickers-hardness increases monotonically with the increasing Cr content in the interesting range. It should be emphasized that the result is chosen by avoiding the grain boundary, which demonstrates therefore the hardening effect of Cr on the grain.

Fig 1. Typical microstructure of the ferritic alloys with various chromium contents (a) 10 wt%Cr (b) 19 wt%Cr (c) 25 wt%Cr (d) 38 wt%Cr.

Fig 2. Vickers-hardness as a function of Cr content for homogenization samples.
3.2. Tensile behavior.

The true strain-stress curves and tensile parameters for the ferritic alloys with various chromium contents are shown in Fig. 3 and Table 2 respectively. It can be seen that the yield strength (σ<sub>y</sub>) increases significantly with the increasing Cr content, which is associated with a slight increasing trend in ultimate tensile strength (σ<sub>u</sub>). Meanwhile, both elongation and reduction of area drop dramatically because of the decreasing toughness. The rich Cr element can strongly affect the strength and toughness, accompanied by more brittle characteristic in the material. Finally, the Fe-38 wt% material fractures before reaching the yield criterion, hence exhibits the lowest σ<sub>u</sub> of 97 MPa due to its extremely low plasticity.

![Graph showing true strain-stress curves for ferritic alloys with various chromium contents.](image)

**Fig 3.** True strain-stress curves for the ferritic alloys with various chromium contents.

**Table 2.** Tensile results of the ferritic alloys with various chromium contents.

| Nominal Cr content, wt.% | σ<sub>y</sub>, MPa | σ<sub>u</sub>, MPa | A, % | Z, % |
|-------------------------|-------------------|-------------------|------|------|
| 10                      | 168               | 333               | 43.5 | 83   |
| 19                      | 284               | 366               | 28.5 | 58   |
| 25                      | 350               | 370               | 4.5  | 5    |
| 38                      | /                 | 97                | 1.0  | 0    |

The fractographs of the room-temperature tensile specimens acquired by SEM technique are shown in Fig. 4. Globally, the toughness of the material decrease significantly along with the increasing Cr content from 10 to 38 wt%, and the fracture mode of the material suffers a transition from ductile to brittle fracture. As shown in Fig. 4(a), Fe-10 wt%Cr alloy shows a significant necking and a large reduction of area at fracture because of good ductility and malleability. Microscopically, the dimple structure is predominantly found, indicating a good toughness. For the Fe-19wt%Cr specimen shown in Fig. 4(b), a boundary is found between the extensive dimple structure and cleavage fracture with river pattern. Then brittle fracture mode dominates in the materials with 25% Cr content, accompanied by only a small part of ductile fracture area. Finally, the material fractured completely by cleavage mode for the alloy with higher Cr content of 38 wt%, due to the extremely low toughness.
3.3. Charpy impact test.

Fig. 5 shows the load-displacement curve during Charpy V-notch impact test of FeCr alloys with various Cr content. It can be seen that the Cr content has little effect on the elastic deformation of the material as their coincidence in the linear elastic stage. However, the impact displacement is greatly reduced with the increasing Cr content and finally reaches a saturation level for high chromium concentration alloy. This phenomenon can be explained by the significant decreasing toughness, which meets the impact energy result.

The impact load-displacement curve is closely related to the material fracture process. From the figure, it can clearly be seen that the Cr content has a great influence on the impact process and fracture mode of the ferritic alloy. For both the material with 10 wt%Cr and 20 wt.% chromium content, plastic deformation occurs before the maximum force, accompanied by partially stable and unstable crack growth. However, the proportion of stable crack propagation in the material with 20 wt %Cr is much higher than that with 10 wt %Cr. As the Cr content increases, the impact curve gradually narrows and becomes steeper at the unloading stage. Eventually, the materials with 25 wt % and 38 wt % chromium content reach the maximum force without yielding, accompanied by small amount of stable crack propagation. Besides, the slope change during the unloading stage is significantly affected by the Cr content. The angle of load-displacement curve at the unloading stage suffers a greatly increase, which indicates the increasing trend in crack propagation speed owing to the reduced toughness.
Subsequently, the impact absorption energy of materials was obtained by analyzing the load-displacement data during Charpy impact test. Globally, the descending trend in impact energy can be seen from Fig. 6 indicating a significant increasing brittleness of the material along with the rising chromium content level.

Theoretically, the total impact energy ($W_t$) in the crack growth process in dynamic fracture can be seen as the addition of crack initiation energy ($W_i$) and crack propagation energy ($W_p$) [16]. In general, the larger $W_p$ is caused by a higher energy consumption and stronger resistance during stable crack propagation process, thus indicating a better toughness. Fig. 6 shows the changes of $W_i$, $W_p$, and $W_t$ with increasing Cr content in detail. It can be seen that all $W_i$, $W_p$, and $W_t$ decrease significantly and stabilize after the chromium concentration reaches 25 wt%. Finally, the $W_i$ approach zero and the proportion of $W_p$ increases significantly. The result indicates that the decreasing influence of Cr content on the impact energy is dominated the crack growth characteristics change of the alloy.

**Fig 5.** Load-displacement curves of Charpy impact test for ferritic alloy with various Cr content.

**Fig 6.** Effect of Cr content on the impact energy values.
In addition, scanning electron microscope TESCAN-5136XM was used to probe the fracture surface of impact specimens and further influence of Cr content on impact fracture mode. The fracture surface of ferrite materials with different Cr content is shown in Fig. 7. Globally, all the impact fractures are relatively flat and exhibit brittle fracture characteristics, except for Fe-10 wt%Cr materials. The detailed analysis shows that the fracture surface of the Fe-10 wt%Cr material is mainly composed of a large number of shallow dimples, while the fracture surface of the Fe-20 wt%Cr sample has coexistence characteristics of brittle fracture and ductile tear feature. Finally, the brittle fracture characteristic becomes more obvious and the fracture surface is fully featured by a typical river-like cleavage fracture with the increase of Cr content.

![SEM fractographs](image)

**Fig 7.** SEM fractographs of Charpy impact test specimens for a) 10 wt%Cr, b) 19 wt%Cr, c) 25 wt%Cr and d) 38 wt%Cr alloy

### 4. Conclusions

In order to investigate the influence of Cr content on the mechanical properties, four ferritic alloys with various Cr content ranging from 10 to 38wt% were firstly prepared. Then the Vickers-hardness and mechanical test results indicate that the high Cr content will cause a hardening and strengthening effect on the ferrite steel. Meanwhile, it can be concluded that the ferritic alloys suffers a reduction of toughness and a failure mode transition from ductile to brittle fracture by conducting the SEM fractography analysis.
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