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Short-term Mechanical Properties of Fe-Cr-Al-Si Alloys

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Abstract

The purpose of this work is to study the short-term mechanical properties of Fe-Cr-Al-Si-based alloys.

Within the framework of this work, alloys with a chromium content of 5 to 14 wt%, aluminum from 0 to 4 wt%, and silicon from 0 to 4 wt% are considered. The samples were tested in three different states - in the deformed state (cold rolling by 80%), and also after annealing at a temperature of 450 and 650 °C with a duration of 1000 h.

As a result, the characteristics of the strength and plasticity of alloys in the deformed state, as well as after provoking annealing, were obtained. It is shown that embrittlement isn’t observed in the investigated composition region and annealing conditions, and the strength of the alloys is directly proportional to the sum of the alloying elements Al + Si.

Keywords: cladding; VVER; tolerant fuel, ferrite steel; Corrosion-resistant steel, tensile strength, yield strength

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1. INTRODUCTION

In present, alloys of the Fe-Cr-Al system are being investigated in the world for their application as cladding [1-3]. The chromium content in these steels ranges from 10 to 20 wt. %, the aluminum content ranges from 3 to 5 wt. %. Such ferritic steels are promising for various applications in the nuclear power industry. Initially, this steels were developed abstractly as radiation-resistant ferritic steels, they are not swelling under irradiation. Futher, the development of steels began in two main directions: cladding for light water reactors as one of the components of ”tolerant” fuel and cladding for fast reactors with a lead coolant [3-8].

However, the main problem of these steels is relatively low strength at high temperatures, as well as embrittlement under irradiation due to the decomposition of the solid solution [8-12]. It is known that aluminum doping to chromium ferrite leads to a narrowing of the spinodal curve of Fe-Cr solid solution decomposition (Fig. 1).

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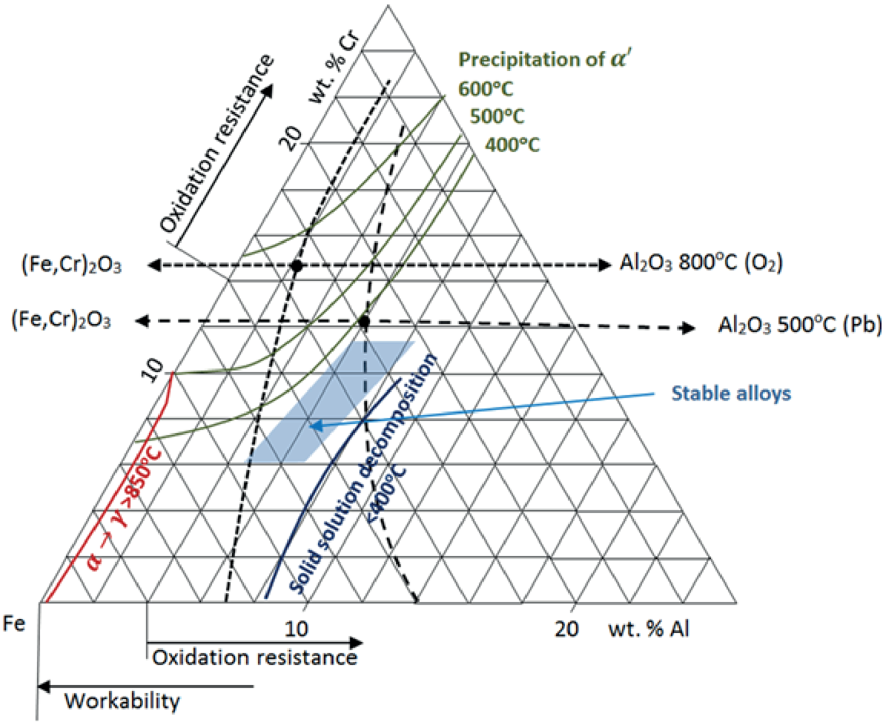

Figure 1: Schematic phase diagram of Fe-Cr-Al system.

Thus, there is question: it is possible to reduce the content of chromium in the steel and alloying it with aluminum and silicon to suppress the embrittlement of such alloys? Therefore, the purpose of this work is determination the short-term mechanical properties of Fe-Cr-Al-Si alloys.

2. EXPERIMENTAL

Model alloys of Fe-Cr-Al-Si systems were obtained by arc melting with a non-consumable electrode in an atmosphere of purified argon. Ingots weighing about 100 g were melted from pure metal powders pressed into briquettes, each ingot was melted 4-6 times to achieve uniformity. All alloys are a homogeneous solid solution based on ferrite. The obtained ingots were subjected to homogenization annealing in vacuum (1200 C, 4 h), then they were forged into a hot square 8x8 mm, which was rolled into a strip 0.5 mm thick along the following route: hot rolling to a thickness of 3 mm, recrystallization annealing 1000 C, 1 h), after which the rolling is cold to a given thickness. From the obtained cold-deformed strip, standard discontinuous samples (working part 20x5 mm) were made. In order to determine the effect of thermal aging on the properties of alloys, all the samples obtained are divided into three groups. The first group remained in the cold-deformed state, the second and third were subjected to long-term annealing at temperatures of 450 and 650 C, simulating the characteristic operating temperatures in the reactor plants, during 1000 h. Also, the temperatures are key for this material, since at 450 C the most the solid solution dissolves intensively in Fe-Cr alloys, and the temperature of 650 °C is the temperature at which the alloys recrystallize.

The initial and aged alloys were tested for uniaxial tension on an Instron tensile machine with a strain rate of $5 \cdot 10^{-2}$ min-1. Based on the test results, the conditional yield strength, tensile strength and total elongation were determined. The temperature dependence of the yield strength was modeled on the basis of the generalized temperature dependence for ferrite and ferrite-martensitic steels.

3. RESULTS AND DISCUSSION

The obtained values of the conditional yield strength, tensile strength, and elongation for the investigated alloys in different states are given in the table 1.

Relatively small number of samples were tested in the work, only one 2-3 for each composition. As is known, the tensile strength is directly proportional to the yield strength. Therefore the dependence of the tensile strength on the yield strength from obtained data is verified and is shown in Fig. 2.

Figure 2.1 shows that the main partof the data is in good agreement with the well-known dependence. The main quantity of the drop-down data is characteristic for alloys annealed at 450 °C. This can be due both to the errors in the installation of samples in the tensile machine and the surface defects on the samples.

The dependence of the relative elongation on the tensile strength for alloys after different heat treatments is shown in Fig. 3.

From the obtained data it follows that alloys with 80% cold deformation are characterizing by a relatively small elongation of 5%. However, annealing for 1000 hours at 450 °C increases the elongation for all alloys to a level of 10%. It should be noted that the recrystallization of alloys does not occur even after prolonged annealing at 650 °C. All alloys in the annealed form (650 °C, 1000 h) have a high plasticity (up to 40%).

To predict the yield strenght from temperature for some of the studied alloys, a phenomenological equation was used. It describes the change in the yield strength of ferritic and ferritic-martensitic steels from temperature [13]:

$$\frac{\sigma(T)}{\sigma(20^{\circ}C)} = 0.027 + 1.575 \cdot \left(\frac{0.4183}{1 + 10^{0.00818\cdot(T+105,79)}} + \frac{0.582}{1 + 10^{0.00365\cdot(T-589.98)}} \right) \tag{1}$$

As the yield strength at room temperature yield strength values annealed alloys was taken.

Table 1: Mechanical properties of alloys tested in this work.

Cr, %	Al, %	Si, %	Cold rolled (80% c.d.)			450°C, 1000h annealed			650°C, 1000h annealed		
			$\sigma_{0,2}$, Mpa	σ_{uts}, MPa	δ_{tot}, %	$\sigma_{0,2}$, Mpa	σ_{uts}, MPa	δ_{tot}, %	$\sigma_{0,2}$, Mpa	σ_{uts}, MPa	δ_{tot}, %
8	1	-	592	617	5,1	452	499	6,6	171	314	37,6
8	2	-	659	690	5,2	453	517	8,6	211	361	39,4
8	3	-	848	905	5,4	513	582	10,3	250	396	35,9
10	1	-	684	733	4,7	505	600	10,5	176	348	43,4
10	2	-	872	899	5,1	546	625	10,5	240	408	41,7
10	3	-	829	873	4,9	582	668	10,0	282	414	40,2
10	4	-	-	-	-	523	612	9,3	320	447	39,6
12	1	-	732	769	5,2	534	625	10,0	204	345	39,9
12	2	-	888	944	4,5	586	731	10,8	247	368	40,4
12	3	-	873	929	4,9	530	780	10,1	307	447	32,1
12	4	-	870	918	4,8	517	700	10,3	341	460	37,4
14	1	-	776	820	4,9	522	739	12,3	220	370	43,9
14	2	-	831	883	5,2	510	835	11,4	260	404	41,1
14	3	-	882	935	4,5	519	858	15,9	318	444	35,7
14	4	-	826	919	4,9	419	670	10,7	356	481	38,1
8	-	1	739	803	4,8	412	772	14,3	244	399	45,5
8	-	2	759	819	4,3	425	771	19,5	309	445	34,6
8	-	3	800	931	3,6	777	806	10,5	388	502	26,4
8	-	4	946	1000	4,3	849	897	10,8	474	589	25,1
10	-	1	690	741	4,6	630	670	11,9	236	385	35,9
10	-	2	746	935	4,7	734	796	13,0	334	461	32,1
12	-	3	703	853	4,7	707	778	11,0	255	392	40,2
14	-	1				849	905	10,1	411	525	24,7
14	-	2	856	901	4,5	724	787	10,7	328	454	31,7
14	-	3	824	1003	4,5	824	950	7,5	425	546	26,5
5	2	2	725	967	4,7	825	875	12,1	453	569	32,8
5	1	3	495	888	4,6	755	802	9,0	386	514	36,9
5	1	4	784,06	983,38	4,6	871	916	10,1	447	562	31,6

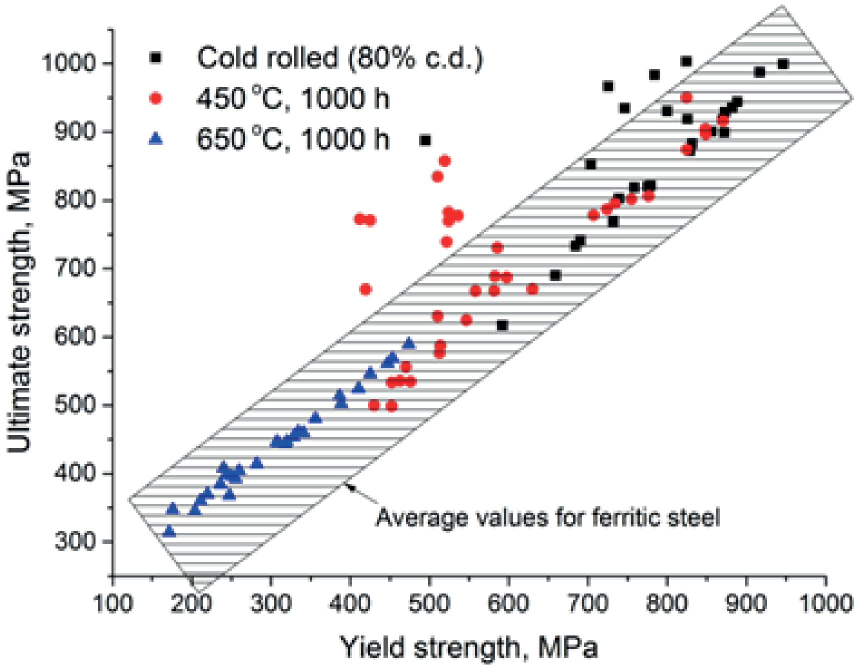

Figure 2: Dependence of the tensile strength on the yield strength for all the alloys studied in different structural states.

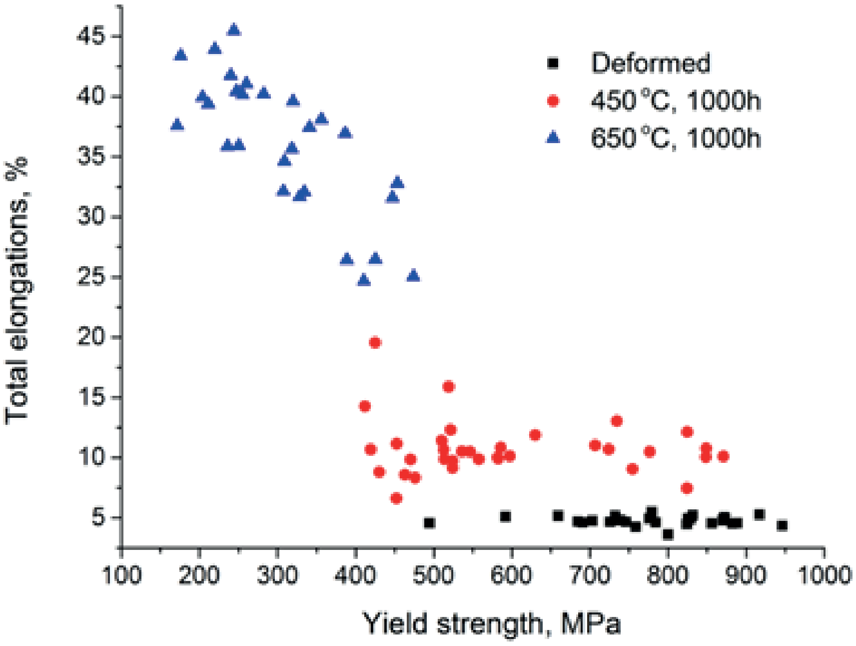

Figure 3: Dependence of the relative elongation for all the investigated alloys in different structural states.

The obtained results are given in Fig. 4. For comparison, data for two materials are presented. This is ferrite-martensitic steel EP823 used for claddings in reactor with a lead coolant and zirconium alloy E110 used for light water reactors.

From the calculated data it can be seen that the most promising alloys from this study have strength at high temperatures sufficient to use them as claddings for light

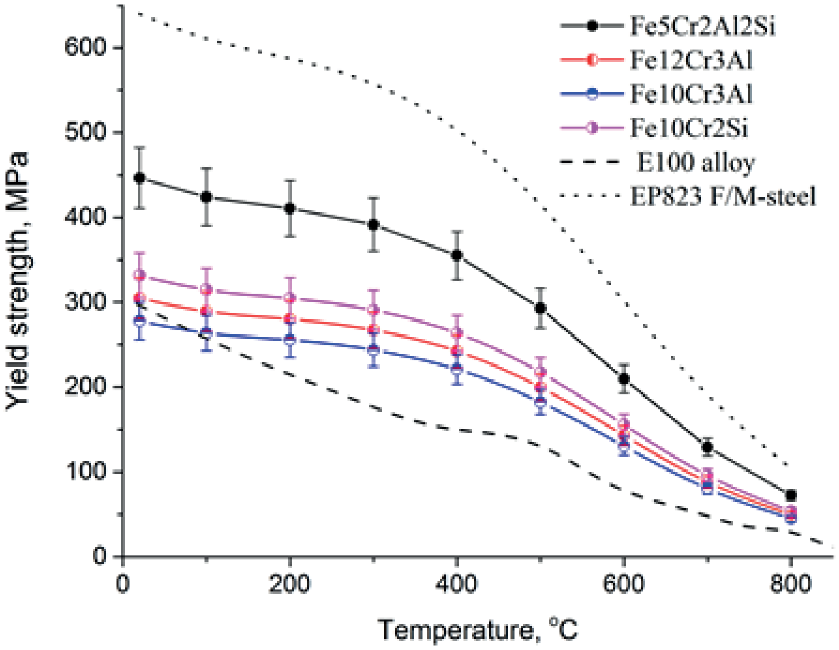

Figure 4: The change in the yield strength at high temperatures for some of the studied alloys in the annealed state.

water reactors. It should be noted higher values of ductility of single-phase Fe-Cr-Al alloys. The same can be said for Fe-Cr-Al-Si alloys. From the obtained results, the possibility of creation alloys with sufficient strength and plasticity are followed.

4. CONCLUSION

1. It is shown that in the investigated concentration range, embrittlement of impurities-free alloys after prolonged high-temperature aging at temperatures of 450 and 650 °C has not been detected.
2. High plasticity (> 30%) in aged alloys has been confirmed.
3. The calculated yield stresses for the most corrosion-resistant alloys confirm the possibility of using this class of materials as a basis for the development of steels for fuel rod cladding of nuclear reactors.

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