





Evaluation of the high-entropy Cr-Fe-Mn-Ni alloys compatibility with a liquid lead coolant

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Technical Meeting on Structural Materials for Heavy Liquid Metal Cooled Fast Reactors, 15-17 October 2019, Vienna, Austria



I.V. Kurchatov



A.I. Leipunsky

Where I am from?

History. NSC KIPT has the deep historical roots. It was created in 1928 by academician A.F. Ioffe and scientists, which arrived from Leningrad.

The Institute is mainly known due to the fact that on October 10, 1932 A.Valter, K.Sinelnikov, A.Leipunsky and I.Latyshev carried out the outstanding physical experiment – they split the nucleus of lithium.

This achievement can be truly considered the starting point of the following dynamic development of nuclear Nob physics, physics of accelerators and nuclear materials science.

The known Soviet physicists L.D.Landau I.V.Obreimov,I.V.Kurchatov,N.E.Alekseevsky,L.F.Vereshagin,E.M.Lifshits, I.M.Lifshits and others worked here.

Up to 1991-Institute served in MinSredmash and was leading organisation in former Soviet Union on Physics of Radiation damage.

The main direction of activity now: to carry out research in science and technology to provide the development of nuclear power engineering in Ukraine.



L.D. Landau Nobel Prize for Physics



K.D. Sinelnikov

Victor Voyevodin, Director of Institute of Solid State Physics, Material Science and Technology NSC KIPT, NASU corresponding member 2



National Science Center "Kharkov Institute of Physics&Technology" National Academy of Sciences of Ukraine

Institute of Solid State Physics, Material Science and Technology

Institute of Plasma physics



Niels Bohr





X. Kamerlingh-Onnes R. J. Van de Graaff
 They worked in KIPT

Institute of Theoretical physics named by A.N.Akhiezer

Institute of Plasma electronics and of new methods of acceleration

Institute of High energies physics and of nuclear physics



Great support to KIPT provided A.F. loffe

«Science-technical complex "Nuclear fuel cycle" Science-researching complex "Accelerator"

Nuclear Energy in Ukraine (current status)

Nuclear production of Ukraine was and remains the only branch of national power which was able during the years of independence to continue the progress not decreasing the production (15 units provide today more than 50% (13835 MWt) of electric power demand). Rv-1

Rovno

Khmelnitsk

Building

2020 ???

Chernobyl

South Ukraine

Rv - 2

Khar

aporozhye

2013

2014

2015

20

2(|))

20

21

- VVER-440

Slovak

Hunce

Poland

- VVER-1000

Black Sea - RBMK-1000 shutdown 2034 Now electricity production by nuclear plants is $\geq 50\%$ of total

Thermal power of Ukraine which experiences now the troubles with the fuel supply has 104 units on its TES and TEC (all of them have operated more than 40 years and 90% of these units have exhausted " the park" resource of 100 thousands hours).

Institute of Solid State Physics, Material Science and Technology of "KIPT" (ISSPMT)



Physics of radiation phenomena and RMS

Pure metals, new materials and technology

Ion-plasma treatment of materials and technology

Carbon-graphite materials

The main focus of research activities is nuclear power and defense industry.

Research & development of modern structural materials in nuclear energetic N. Azarenkov, I. Neklyudov, V. Voyevodin

The examples of degradation phenomena Swelling and deformation of austenitic materials



National Science Center "Kharkov Institute of Physics and Technology" Research & development of modern structural materials in nuclear energetic N. Azarenkov, I. Neklyudov, V. Voyevodin

Example of embrittlement arising from void swelling in AISI 321* in BOR-60



All broken during refueling operations

National Science Center "Kharkov Institute of Physics and Technology" Ion issues on irradiation behavior of structural materials at high doses and gas concentrations

Swelling of ferritic-martensitic steels EP-450 irradiated to super-high doses





Swelling of BCC steels may reach more than 20% at super-high doses;

Ferritic grains in EP-450 begin swell early than sorbite one;

Average swelling rate depends on volume ratio of ferrite to sorbite grains;

The rate of swelling on steady-state stage is 0,2%/dpa that agreed with observed swelling of binary Fe-Cr alloys irradiated in EBR-II and FFTF.



Swelling behaviour of ASS and F/M steels KIPT data (1984-2016)

For the first time the irradiation and comparison of swelling data for austenitic and ferritic alloys at 0-300 dpa have done



(Voyevodin et.al, 12th International Workshop on Spallation Materials Technology,19-23 October 2014, Bregenz, Austria)

Austenitic alloys were irradiated with ions ~25 years ago, but were not published in the West.

F/M alloys were irradiated in the last 5 years.

Bcc iron-based alloys have longer swelling incubation period and lower swelling per dpa rate (~0.2%/dpa) in steady –state void growth region than do simple fcc iron-based alloys (~1%/dpa)

Advantages of simulation experiments

Electrostatic (3-beam) accelerator with internal injector (ESUVII)

Irradiation	Parameters			
Cr Cr+He Cr+H Cr+He+H	$\begin{split} & E_{Cr} = 0.3 - 1,8 \; \text{MeV} \\ & j_{Cr} = 1 - 35 \; \mu \text{A/cm}^2 \\ & E_{He} = \; 10 - 60 \; \text{keV} \\ & j_{He} = 1 - 500 \; \text{nA} \; /\text{cm}^2 \\ & E_{H} = \; 10 - 60 \; \text{keV} \\ & j_{H} = \; 1 - 500 \; \text{nA} \; /\text{cm}^2 \end{split}$	T $_{irr}$ = 350° - 800°C D = 0 - 1200 dpa k = 7·10 ⁻⁵ - 2·10 ⁻² dpa/s 0.1 - 1.3 appmHe/s 0.1 - 1 appmH/s		
200 dpa	300 dpa	450°C	500 dpa 30 % 6,1 % 1 <u>000 mm</u>	のないので、「ない」のないで、「ない」ので、「ない」ので、「ない」ので、「ない」ので、「ない」ので、「ない」ので、「ない」ので、「ない」ので、「ない」ので、「ない」ので、「ない」ので、「ない」ので、
HT9 at	450°C 500	dpa 600 dpa	200 nm 14YWT	

Providing of reliability and durability of Zirconium items for VVER reactors

A.S. Kuprin, V.A. Belous, V.N. Voyevodin, V.V. Bryk, R.L. Vasilenko, V.D. Ovcharenko, E.N. Reshetnyak, G.N. Tolmachova, P.N. V'yugov. Vacuum-arc chromium-based coatings for protection of zirconium alloys from the high-temperature oxidation in air // Journal of Nuclear Materials 465 (2015) 400-406





Oxidation in air of fuel elements (E110 and Zr1Nb)

Inadmissibility of severe consequences in case of loss of coolant accident (Fukushima-1); 1020 °C Creating a protective barrier layer to preserve the integrity of the fuel rods require that the coatings: ✓ high corrosion and radiation 1100 °C resistance; ✓ improve the mechanical characteristics of zirconium products; ✓ stability of functional properties at high temperaturesT = 350...1100 °C.

The defect-free nano-structural radiation- and temperature resistant coatings (Cr, SiC, FeCrAI) with high mechanical and corrosion properties were created that ensure durability and integrity of cladding of fuel elements during operation and in an accident up to 1100 ° C.

Five-fold reduction in swelling of 18Cr10NiTi ODS steel (D=100 dpa, T_{irr}=615 °C, E=1.8 MeV Cr³⁺)



Strength of sinks – radiation resistance of steel

High density of boundaries and boundaries in fine grains may maintain the high density of traps for recombination of defects.

for oxide:
$$S_0 = 4\pi N (0.3A^{1/2})$$

for boundary: $S_b = \frac{15}{h^2}$

where So is the sink strength contributed from oxides, *N* is the number density of the oxides, *A* is the surface area of the oxides, $A = 4\pi r^2$, *r* is the average radius of the oxides, *Sb* is the sink strength contributed from grain boundaries, and *h* is the average grain size.



Efficiency for oxide is 35 times higher than grain boundary

 $S_b = 1,41 \cdot 10^{13} \text{ m}^{-2}$

 $S_o = 4,86 \cdot 10^{14} \text{ m}^{-2}$

Generations of nuclear energetics reactors



The main impact factors on construction materials: Radiation (dose, dose rate), Temperature, Stress, Environment For each type of reactor, these factors quite differ

Heavy Liquid Metals (HLM) Systems



General properties of HLM

Good nuclear and thermal-physical prope High thermal efficiency	erties
High boiling temperatures	
Wide range between melting and	boiling
temperatures	Ū
Low vapor pressure	
High heat transfer coefficient	
Low melting point	

Coolant	Melting point (°C)	
Pb	327.4	
Pb-17Li	235	
Pb-Bi	123.5	

Properties of liquid-metal media for LFRs

Liquid Metal	Advantages	Disadvantages	
Pb $T_m = 327^{\circ}C$ Coolant Pb-Bi (LBE) $T_m = 123^{\circ}C$ coolant and/or spallation target	 High spallation neutron yield Low γ-radioactivity induced in Pb and Pb-Bi Low neutron moderation and capture Chemical inertness with water Neutron multiplication 	 High corrosion aggressiveness Liquid Metal Embitterment (LME); Production of a-radioactive volatile ²¹⁰Po from Bi and Pb – hazard for the environment 	

Main problem: Compatibility of structural materials with the liquid metals !!!

Interaction between solid and liquid metals

Dissolution - basic interaction phenomenon!

Weeks - 1962



Corrosion process in liquid metal is characterized by:

- 1. Selective dissolution of solid metal in liquid one;
- 2. Diffusion processes in solid metal;
- 3. Penetration of liquid metal in solid one, inner oxidation;

Lyublinski et al., JNM 224 (1995) 288



A preferential dissolution of chromium and nickel is observed. Solubility limit of nickel is 100 times higher than Fe and Cr.

Corrosion/oxidation of steels in Pb/Pb-Bi (earlier studies)



Materials Issues

V. Tsisar et al. Int. workshop "Materials resistant to extreme conditions for future energy systems", Kyiv, 2017

- Pb and Pb-Bi corrosion environment
- > Oxygen control. Low pressure is an advantage
- Erosion (m/s range)
- High fast neutron fluences (4·10²³ n/cm² limit)
- Especially for higher temperatures
- Long-core life (corrosion, creep, TF, etc)
- High reliability (limited inspection, core battery)

Known materials up high temperatures (> 500°C), evolutionary or new materials to be qualified !

Development of new materials is a very time consuming process ! Use as much as possible of available materials...



Austenitic SS: Solid solution with carbides on grain boundaries and a few in matrix Tempered Martensite: Carbides on grain boundaries, subgrain boundaries, and ferrite matrix

HEA's - general and properties

(HEA's) — new type of alloys which contain not less than 5 elements, moreover quantity of each of them must not exceed 35 % and must not be less 5 at%. For such alloys are characteristic increased values of entropy of mixiing Smix in comparison with traditional multi component alloys. Classic examples of HEA's are multi component alloys where elements are in equal atomic fraction [1] High-entropy alloys are presented as special group because processes of structure and phase formation also as diffusion mobility of atoms, mechanism of formation of mechanical properties and thermal stability differ considerably from analogous processes in traditional alloys. The latest are alloys with base elements (Fe, Ni, Mo, Al and others), which determine crystalline lattice of material.

Phase composition of such alloys may be easily forecasted on the base of double or triple <u>constitution diagrams</u> and introduction of alloying elements leads to solid solution hardening of initial lattice or to precipitation in it of dispersed phases...

HEA's examples with different crystal lattice

FCC Alloys of CoCrFeMnN system (equal atomic fraction - Kantor's alloy) CrCuFeNi₂Al_{0.5}; Cr_{0.18}Fe_{0.36} Mn_{0.21}Ni_{0.15}Al_{0.10} et al. BCC HfNbTaTiZr; MoNbTiVZr; MoNbTaVW; AlNbTiV et al. HCP MoGdHoTbY; DyGdHoTbY; MoPdRhRu et al

High entropy alloys publications activity



Ratio of the number of publications under the heading "high-entropy alloy" to the total number of Elsevier publications keeps increasing dramatically since 2009, suggesting the prominence of this new alloy design philosophy. In absolute numbers, 900 papers were published in 2018. (data from the *Web of Science*)

High entropy alloys (HEAs)

HEAs – multicomponent alloys with near equiatomic concentration that remain in solid solution. There is no "principal" element!



Configurational entropy of mixing ΔS_{mix} **and Gibbs energy** ΔG_{mix}



Swelling in FCC alloys with different number of components

K. Jin et al. / Scripta Materialia 119 (2016) 65-70



• Chemical disorder-induced change in vacancy diffusion

25

• *High localized atomic level stress -> damage healing*

Radiation induced hardening of E32-2 (Cr₂₀Fe₄₀Mn₂₀Ni₂₀)HEA irradiated by Ar ions



The radiation hardening of HEAs is much less than that of traditional materials for nuclear energy (austenitic steels 18Cr10NiTi and SS316); therefore, they are less susceptible to radiation embrittlement **26**

Materials - preparation and procedures



Components purity > 99.9%. Arc melting in argon atmosphere. Ingots were re-melted 5 times for homogeneity Stage rolling (true deformation 40% per step) + intermediate annealing at 1100°C 3h Final annealing at 850°C and 1050°C for 3h

Alloy	Cr	Fe	Mn	Ni	
E30-2	18	40	28	14	NSC KIPT alloy
E31-2	18	27	27	28	Similar as Oak Ridge alloy
E32-2	20	40	20	20	NSC KIPT alloy

Corrosion test equipment



Corrosion test schematics

Determination of oxygen concentration in liquid lead

Oxygen concentration in liquid lead is calculated from the partial pressure of oxygen in the gas medium for certain temperatures. Formulae with correction for partial pressure of oxygen:

 $\log C_{max} = 1/2 \log p_{0_2} + 4.67 - 5350/T (327 - 540^{\circ}C); \quad \log C_{max} = 1/2 \log p_{0_2} + 4.57 - 5260/T (540 - 850^{\circ}C)$



Dependence of the oxygen concentration in the liquid lead on the oxygen pressure in Ar atmosphere above the melt for various temperatures

Original alloys microstructure (final annealing at 850°C and 1050°C)



Annealing at 1050°C \rightarrow oxides precipitations dissolution + growth of grain size (2-7µm \rightarrow 40 µm and above)

Structure of the matrix and the surface layer of alloys after 1000h exposure at 480°C

Cr₁₈Fe₂₇มปก₂₇ปก่₂₈

Elements distribution on the surface layer of E32-2 alloy (500h exposure at 480°C)

Data confirms the dissolution process of Cr, Ni, Mn and Fe in a liquid lead and their concentration changes in the surface layer of the matrix

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Elements concentration in the surface layer of the lead and matrix (1000h exposure at 480°C of E32-2 alloy)

Area 2 Cr. Fe enriched

Электронное изображение 1

Электронное изображение 1

|--|

Elemen	%wt	%at
t		
Cr K	0.98	3.38
Mn K	0.79	2.57
Fe K	3.07	9.85
Ni K	0.86	2.61
Pb M	94.31	81.59
Total	100.00	

4	rea	2

200мкр

%wt	%at
30.91	33.78
9.78	10.12
38.10	38.77
16.61	16.07
4.60	1.26
100.00	
	%wt 30.91 9.78 38.10 16.61 4.60 100.00

	20

Электронное изображение 1

Area 3

Elemen	%wt	%at
Ċ		
Cr K	17.36	18.54
Mn K	18.88	19.09
Fe K	42.03	41.81
Ni K	21.73	20.56
Pb M	0.00	0.00
Total	100.00	

Main mechanism of corrosion damage at 480°C - intergranular corrosion (etching of grain boundaries, dissolution of Cr, Ni and Mn in liquid lead and lead penetration into the matrix)

Growth kinetics of lead surface layer enriched with elements of alloys at 480°C

Growth kinetics of lead surface layer enriched with elements of alloys confirms the mechanism of dissolution elements from matrix to lead

Structure of the near surface layer of E32-2 alloy after 1000h exposure at 580°C

E30-2 Cr₁₈Fe₄₀Mn₂₈Ni₁₄

E32-2 Cr₂₀Fe₄₀Mn₂₀Ni₂₀

Combined mechanism of corrosion damage at 580°C: intergranular corrosion + oxygen diffusion from the melt into the matrix \rightarrow internal oxidation of Cr and Mn 35

Structure of the surface layer of alloys after 500h exposure at 580°C

ב30-2 Cr<u>i</u>sFe₁₀אוו<u>י</u>נווע

E31-2 Cr<u>is</u>Fe<u>2</u>7ที่บ<u>2</u>7ไป

ב<u>32-2</u> Cr20Le³⁰Li³⁰Cr³⁰Le³⁰Li³⁰

The dissolution of the matrix elements in the surface layer of lead is realized. The next step is the dissociation and dissolution of the chromium and manganese oxides in the matrix and, as a result, the hardness in this surface zone is decreased. Simultaneously activated diffusion of oxygen from liquid lead in the alloy matrix, causing intergranular oxidation. The depth of corrosion zone is minimal in E32-2 alloy.

E32-2 alloy (Cr₂₀Fe₄₀Mn₂₀Ni₂₀) is most corrosion resistant from investigated alloys!!!

Changes in hardness of the surface layers and matrix of E32-2 alloy on the exposure time at 480°C and 580°C

Dose dependence of the nanohardness of the initial and irradiated E32-2 and E32-2 ODS alloys

E32-2 Cr₂₀Fe₄₀Mn₂₀Ni₂₀

E32-2 ODS Cr₂₀Fe₄₀Mn₂₀Ni₂₀ (Y₂O₃-ZrO₂ mech. alloyed)

The change in the hardness of the E32-2 ODS alloy under irradiation is much lower than that in original as-cast alloy due to the presence of nanosized oxide precipitations

As a rule, selective dissolution of its components is observed upon contact of a complex alloy with a liquid metal.

The thermodynamic activities of the steel components are the main characteristics that determine their tendency to selective dissolution in liquid metal.

The thermodynamic activity of the alloy component will be minimal in solid solution with a crystallographic structure that corresponds to its own lattice. For example, in austenitic steels, nickel having a HCC-lattice has low activity (<1) and chromium (BCC-lattice) has a much higher activity factor (2–3).

Thus, based on the analysis of the presented results, it can be argued that at a temperature of 580 ° C two parallel processes are realized. The first, as at 480 ° C, is the dissolution of Cr, Mn, Ni elements in the near-surface layer, the dissociation and dissolution of the chromium oxides present in the matrix and, as a result, the reduction of hardness in the near-surface zone. In parallel, the opposite diffusion of oxygen from the lead melt into the alloy matrix is activated, which causes internal oxidation. This process takes place at some distance from the surface and, with increasing exposure, extends into the depth of the matrix. It can be assumed that the cause of this process, which begins at a certain distance from the surface, is a decrease in the concentration of Cr, Mn due to their dissolution in lead. It can be assumed from the previously obtained micro-ray spectral analyzes that the process of internal oxidation consists in the formation of Cr and Mn oxides.

Conclusions

- Conducted research showed that HEAs can be served as promising structural materials for Gen-IV reactors.
- It was established that for all studied alloys compositions at 480°C the main mechanism of corrosion damage of the surface layers is intergranular corrosion, which consists in the etching of grain boundaries, lead penetration into the matrix and dissolution of chromium, nickel and manganese in liquid lead.
- ✤ Increasing the temperature to 580°C contributes to the implementation of the combined mechanism of corrosion damage, which is realized by the combination of intergranular corrosion, as well as at a temperature of 480°C, and the diffusion of oxygen from the melt into the matrix and, as the result, implementation of the internal oxidation of chromium and manganese process.
- Using these alloys in contact with the lead melts can be recommended to a temperature of 500°C, moreover, E32-2 alloy (composition Cr₂₀Fe₄₀Mn₂₀Ni₂₀) has an advantage.
- Possible options for increasing the operating temperature are optimization of the HEAs composition and additional alloying. Oxides forming elements? ODS HEA???

Thank you cordially for patient and attention !

Determination of oxygen concentration in liquid lead

Oxygen concentration in liquid lead is calculated from the partial pressure of oxygen in the gas medium for certain temperatures. Formulae with correction for partial pressure of oxygen:

 $\log C_{max} = 1/2 \log p_{0_2} + 4.67 - 5350/T (327 - 540^{\circ}C); \quad \log C_{max} = 1/2 \log p_{0_2} + 4.57 - 5260/T (540 - 850^{\circ}C)$

Dependence of the oxygen concentration in the liquid lead on the oxygen pressure in Ar atmosphere above the melt for various temperatures

Plan for further research

- 1. Corrosion studies in eutectic Pb-Bi
- 2. Corrosion studies with different oxygen content in lead melts.
- 3. Corrosion studies at higher testing temperatures
- 4. Investigation of corrosion-mechanical characteristics in lead melts (short-term and long-term durability, fatigue life).
- 5. Modified materials: oxides forming elements, ODS HEA....

Corrosion behaviour of Cr18Ni10Ti steel in molten lead at 550 °C

500 h

1000 h

Structure of the near surface layer

Elements distribution in near surface layer after 500h and 1000h exposition at 550 °C

	Area 1	
Element	Weight %	Atomic %
Cr	0.07	0.26
Mn	0.10	0.38
Fe	1.12	4.00
Ni	0.28	0.94
Pb	98.42	94.42

Area 2					
Element	Weight %	Atomic %			
Cr	19.23	20.42			
Mn	1.40	1.41			
Fe	72.21	71.42			
Ni	7.17	6.74			

Exposition 500 h

Area 3			Area 4		
Element	Weight %	Atomic %	Element	Weight %	Atomic %
Cr	7.47	14.23	Cr	20.10	21.33
Mn	0.96	1.74	Mn	1.83	1.84
Fe	27.68	49.11	Fe	71.23	70.39
Ni	3.61	6.09	Ni	6.85	6.44
Pb	60.28	28.83			

Exposition 1000 h

Interaction between solid and liquid metals II

As a rule, selective dissolution of its components is observed upon contact of a complex alloy with a liquid metal.

The thermodynamic activities of the steel components are the main characteristics that determine their tendency to selective dissolution in liquid metal.

The thermodynamic activity of the alloy component will be minimal in solid solution with a crystallographic structure that corresponds to its own lattice. For example, in austenitic steels, nickel having a HCC-lattice has low activity (<1) and chromium (BCC-lattice) has a much higher activity factor (2–3).

Як правило, при контакті складнолегованого сплаву з рідким металом спостерігається селективне розчинення його компонентів.

Термодинамічні активності компонентів сталей є основними характеристиками, які визначають їх схильність до селективного розчинення у рідкому металі.

Термодинамічна активність компонента сплаву буде мінімальною у твердому розчині з такою кристалографічною будовою, яка відповідає його власній ґратці. Наприклад, в аустенітних сталях нікель, який має ГЦК–ґратку, володіє низькою активністю (< 1), а хром (ОЦК–ґратка) має значно вищий коефіцієнт активності (2–3).

The kinetic factor also plays a significant role in dissolution. Due to the selective dissolution of one of the alloy components, a layer depleted of this element is formed on the surface of the solid metal. The formation of such a layer promotes phase transformations. For example, austenite in chromium-nickel steels can be converted to ferrite by contact with Pb, PbBi, and PbLi melts.

The presence of nickel, as the most soluble component, is not the only cause of the selective corrosion of steels and alloys based on iron in heavy metal melts. It has been experimentally proved that chromium doping also has an ambiguous effect on the corrosion resistance of steels. Thus, a study of lead-free nickel steels with different concentrations of chromium found that alloys with low chromium content were more stable in liquid lead than high-alloyed ones. As a rule, selective dissolution of its components is observed upon contact of a complex alloy with a liquid metal.

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При взаємодії свинцю з киснем утворюється ряд оксидів. Найбільш стабільним є оксид PbO, який має температу

Ferritic-Martensitic (F/M) steels -main candidate of structural materials in advanced nuclear reactors

Superior Properties:

- Thermal conductivity
- > Thermal expansion coefficient

Need to investigate:

<u>Swelling Resistance</u>
Resistance to He/H embrittlement
Resistance to irradiation creep

Chemical composition of investigated steels:

F/M steels

EP - 450: Fe-13Cr-2Mo-Nb-V-B-0,12C (F+M) *EP - 823*: Fe-12Cr-Mo-W-Si-V-Nb-B-0,16C (M+F) *HT-9*: Fe-12Cr-Ni-Mo-W-V-0,20C (M+F) *EK-181*: Fe-11Cr-Si-Mn-Mo-V-2W-Nb-Ni-B-0,14C (M+F)

ODS alloys

MA957:Fe-14Cr-Si-Mn-Mo-Ni-B-0,01C+ $(1,05Ti-0,25Y_2O_3)$ *14YWT*: Fe-14Cr-3W-Mn-0,06C+ $(0,4Ti-0,25Y_2O_3)$

Philosophy in time

Origin - X18H10T(18Cr10NiTi)

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Dependence of the oxygen concentration in the molten lead on the oxygen pressure above the melt for various temperatures

Solution-based corrosion modes

Leaching of steel constituents by liquid metal

Selective leaching

(a) Solution-based attack is controlled by the Cr diffusion in the near surface layer of steel;
(b, c) Solution-based attack is controlled by the diffusion in boundary layer of liquid metal.

(C)

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The sequence of loading the samples

- 1. Placement the samples into ampoules.
- 2. Loading solid lead and ampoules with the samples into the chamber.
- 3. Pumping vacuum and argon filling the chamber.
- 4. Heating to 350 °C.
- 5. Fill the ampoules by lead.
- 6. Cooling to 20 °C the ampoules in the chamber.
- 7. Discharge the ampoules and their placement into the protective ampoules with their subsequent welding.
- 8. Loading the furnace.
- Exposure at a set temperature and exposure.
 Cooling the ampoules.
- 11. Opening the protective ampoules.
- 12. Transfer the ampoules with samples into the chamber and removal the samples from lead.13. Further metallographic research.

The chamber

There are two ways to reduce the corrosion of metals in the liquid ones.

The first one lays in the using of metals with very low solubility in the liquid (e.g. molybdenum or tungsten).

Another way lays in the formation on the steel surface the protective oxide layers using the oxygen as a special admixture in the liquid metal. Formation of the oxide layers inhibits the dissolution of the steel components provided that the properties of the oxide layer are satisfactory. In general the oxide layer to be protective must posses by the optimal parameters (be adherent, compact, coherent etc) and ability to self-healing during long period of work.

The quality of the coating depends on the level of oxygen activity in the heat medium, composition and structure of the solid material and character of the surface treatment.