Degradation of austenitic steel 12X18H10T after electron beam impact

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Abstract. The surface structural phase changes by continuous electron beam impact on construction steel 12X18H10T were studied in this paper. As a generator of plasma-beam discharge was used device tokamak. The main objective of the work on the simulation bench was to obtain data on the structural materials samples’ surface degradation degree under the influence of exposure to the electron beam and plasma discharge. Scanning electron microscope was used to study the surface morphology after continuous electron beam impact of the steel. As the matter of fact, the energy of electrons was quite low (less than 5 keV), consequently radiation defects were not formed and the entire beam energy went into heating of the target. The built-in modules of transient thermal and steady-state thermal temperature were found to be used numerically as the solution of the problem connecting with arbitrary geometry samples.

1. Introduction
The main goal of the Kazakhstan Material Research tokamak (KMT) is to conduct experimental research and testing of materials and structural solutions to protect the first wall, divertor plates and receiving nodes divertor in the mode of operation close to the ITER [1].

In support of the research program at the Kazakhstan Material Research tokamak KMT was created simulation test bench (STB). A generator is used to generate plasma, which operates on the basis of plasma-beam discharge. Experiment on irradiated samples by continuous electron beam was conducted at the current facility [2]. Tokamak has demonstrated excellent plasma confinement capability because of their symmetry but has an intrinsic drawback because of their pulsed inductive operation. Efforts have been made in the past 20 years to realize steady-state operation, the most successful utilizing a bootstrap current. In this review, progress in understanding tokamak physics related to steady-state operation is described to investigate the scientific feasibility of a steady-state tokamak fusion power system.

It is well known that radiation may significantly affect molecular materials even for relatively small doses [3]. Inter and intra-molecular reactions may promote crosslink and reticulate network in a macromolecular structure, either natural or synthetic, which has been irradiated. For instance, ionizing irradiation of a polymeric material is able to break chemical bonds and introduce modification in the material behavior [3-5]. Several works [6-11] have shown that macromolecular products such as...
natural fibers, biomaterials and polymers may improve their properties by ionizing irradiation as a result of crosslinking and scission processes, in which radicals are formed throughout the chains.

2. Experimental details

18-10 type steel, comprising about 18% chromium and 10% nickel (12H18N9, 10H18N10T, 10812X18H10T at alias) is the main group. Alloying nickel - element extending γ region, leads to the fact that steel 18-10 become austenitic.

Table 1. Chemical composition in % of steel 12X18H10T.

| C  | Si  | Mn  | Ni  | S   | P   | Cr  | Cu  | -   |
|----|-----|-----|-----|-----|-----|-----|-----|-----|
| to 0.12 | to 0.8 | to 2 | 9-11 | to 0.02 | to 0.03 | 17-19 | to 0.3 | (5 C-0.8) Ti, others are Fe |

In the simulation stand KMT uses plasma generator based on beam-plasma discharge (BPD) of low pressure at which the electron beam along the magnetic field is injected into the drift chamber interaction.

Compensated electron beam is transported in the electronic mode (without gas overlap, at extremely low residual pressure) on the target in a longitudinal magnetic field. It can vary within wide limits as the total power (30 kW) and the heat flux on the surface of the test materials. This provides a very wide range of thermal experiments, as well as the possibility of annealing of the samples and studying their thermal desorption.

A sample of steel 12X18H10T fastened with special plates for uncooled graphite target. To control the temperature of the sample on the back side was set XA type thermocouple. Facing the beam of the sample’s surface was polished mechanically.

Table 2 shows the parameters of the unit under test of sample.

While irradiating of steel sample maximum power electron beam was equal to 75 Watts of heating power at the cathode-heated unit (CHU) 130 Watts. The maximum temperature of the steel sample registered by installed thermocouple reached 920 °C.

Appearance of the sample after irradiation is shown in Figure 1.

Figure 1. a) Photo of the sample after irradiation, b) micrograph of the footprint of the beam (SEM) (center).
Studies of samples’ surface morphology after continuous electron beam impact were carried out on a scanning electron microscope JEOL JSM-6390LV with the prefix energy dispersive microanalysis INSA Energy.

Four heat-affected zones are clearly distinguished in the micrograph (Figure 2). In the central zone (Figure 3) precipitates titanium plates are clearly visible. Table 3 shows the analysis of the elemental composition of titanium plates and areas without isolation. The experiment shows that in the scope of the electron beam is formed thin films islet Ti. The film thickness must be less than 1.3 microns, as microanalysis shows the titanium’s content is of about 98 %. If the film was thinner, microanalysis would show the content of other elements due to the "highlight" of the matrix.

![Microphotography of sample after irradiation, SEM x30.](image)

**Figure 2.** Microphotography of sample after irradiation, SEM x30.

**Table 2.** Parameters of the experiment at the 130W heating power CHU.

| CHU | Electron beam | Duration of exposure (min) | The target temperature (°C) |
|-----|---------------|----------------------------|-----------------------------|
| Voltag eU(V) | Current I(mA) | Power N(W) | Voltag eU(kV) | Current I(mA) | Power W(W) |
| 650  | 200           | 130        | 3            | 25           | 75         | 2          | 920       |
Figure 3. Microphotography of the 1st zone (center) x1500.

Table 3. Elemental analysis, in %.

| Spectrum  | Si  | Ti  | Cr  | Fe  | Ni  | Total |
|-----------|-----|-----|-----|-----|-----|-------|
| Spectrum 1| 98.49 | 1.51 | 1.00 | 1.51 | 100.00 |
| Spectrum 2| 95.89 | 2.54 | 2.00 | 2.54 | 100.00 |

Some islands have a complicated structure as nuclei crystallites. Segregation also occurs at the boundary of the 2nd and 3rd zones of Ti based alloy but in a form of cubic isolation on the surface. Table 4 shows the elemental analysis of the domains identified in Figure 6 b.

Figure 4. Boundary of 2nd and 3rd zones. x 900.

Table 4. Elemental analysis, in %.

| Spectrum  | Si  | S  | Ca  | Ti  | Cr  | Fe  | Ni  | Total |
|-----------|-----|----|-----|-----|-----|-----|-----|-------|
| Spectrum 1| 0.29 | 0.29 | 95.89 | 2.54 | 1.00 | 100.00 |
| Spectrum 2| 2.53 | 3.14 | 3.47 | 62.95 | 27.91 | 100.00 |
Recrystallization occurs in the third zone (Figure 6), the temperature was -1300 °C. Also, there are crystals Ti, but much less and smaller in size than on the boundary 2nd and 3rd zones and in the 1st zone.

![Figure 6](image)

**Figure 5.** Microphotography of third zone from 750 to 4500-fold magnification.

The figure 5 shows the boundary of the third and fourth zones. Table 5 shows the analysis of the spectra indicated in the figure.

| Spectrum | Si    | P     | Ti    | Cr    | Fe    | Ni    | W     | Total  |
|----------|-------|-------|-------|-------|-------|-------|-------|--------|
| Spectrum 1 | 0.81  |       | 42.21 | 4.85  | 41.20 | 10.93 |       | 100.00 |
| Spectrum 2 |       |       | 55.24 | 4.75  | 29.79 | 7.71  | 2.52  | 100.00 |
| Spectrum 3 | 1.30  | 0.59  | 21.82 | 6.21  | 53.36 | 16.72 |       | 100.00 |
| Max.     | 1.30  | 0.59  | 55.24 | 6.21  | 53.36 | 16.72 |       | 2.52   |
| Min.     | 0.81  | 0.59  | 21.82 | 4.75  | 29.79 | 7.71  |       | 2.52   |
The sample was cut at the center and the elemental analysis was carried out on depth. Figure 7 shows transverse section border of 2\textsuperscript{nd} and 3\textsuperscript{rd} zones photograph, graph of the intensity of element concentrations depending on the distance was plotted. From this it follows that towards the surface and at grain boundaries, the concentration of Ti significantly increases.

3. Discussion of results
Due to the fact that the energy of the electrons was quite low (less than 5 keV), radiation-induced defects are not formed, and the entire beam energy goes into heating of the target. Thus structural phase changes the surface of the samples - the result of heat exposure of the electron beam.

Software system of finite-element analysis ANSYS 13.0 was used to build the model, working on the basis of the geometric core Parasolid.

Solution of the problem for an arbitrary geometry samples was found numerically using the built-in modules Transient Thermal and Steady-State Thermal. Material samples were 12X18H10T steel. The
dimensions of the finite element model and the physical and technical data in both versions were introduced in Appendix Mechanical. Characteristics of the model are shown below.

**Table 6.** Characteristics of the model.

| Characteristic                        | Value                                      |
|--------------------------------------|--------------------------------------------|
| Dimensions of the sample:            | 50×10×1 mm;                                |
| Density of steel:                    | 8055 kg/m³;                                |
| Thermal conductivity:                | 13.8 W/m °C;                               |
| Specific heat:                       | 480 J/kg °C;                               |
| Weight of steel sample:              | 40.2·10⁻³ kg;                              |
| Initial temperature:                 | 22 °C;                                     |
| Radius of the spot heating:          | 1·10⁻³ m;                                  |
| Heat flux density:                   | ~1.9·10⁻⁷ W/m²;                            |

Figure 8 shows a fragment of the program showing the simulation grid. The grid was generated automatically, mesh size was set manually to 1 mm. Mesh was obtained consisting of 4724 elements.

![Figure 8. Generation of grid model in Ansys 13.0.](image)

Each step of the pattern corresponds with one second of heating, 1000 iterations were taken for decision and construction of the temperature distribution during heating.

Figure 9 shows the parts of the program, showing the graphical results of calculations. Figure 9 designated temperatures at random points located around the spot heating are illustrated on the figure. The temperature scale is shown on the left.

Figure 9 shows the result of calculation with regard to the embodiment of the contacting surfaces. It is seen that the spot diameter is ~ 3 mm. Unbalanced spot, the temperature distribution with strong edge effects are shown.
Figure 9. The results of temperature field calculation with the contacting surfaces.

Figure 10 shows a fragment of sample geometry with temperature distribution through the thickness of the sample in the embodiment with the contact surfaces. The cut is made at a distance of 0.1 mm from the center of heating spot. It is seen that the presence of the contacting surfaces leads to diameter reduction, and the overall appearance of the temperature distribution also changes.
Figure 10. Temperature field of the sample cross-section in the presence of the contact surfaces.

Figure 11 is a graph, which shows the temperature change in the center of the heating spot for 20 steps, which corresponded to 20.

Figure 11. Dependence of temperature spots in the center on time.

Figure 12 and Figure 13 shows the temperature distribution along the height of the sample for two embodiments. The distance is measured from the center of the spot on the surface into the sample.
Figure 12. The temperature distribution in height of the sample in the second embodiment.

Figure 13. The temperature distribution along the length of the sample in the second embodiment.
Isolation of impurities can be explained by the presence of gradients of point defects near the border. Due to the intense heat after turning off the electron beam occurs excess thermodynamic equilibrium vacancies. As a result, the flow of vacancies occurs, which is directed perpendicular to the surface and from the scene of the beam. The metal border is intensive sink of vacancies, so the average profile of the distribution of vacancies at the border changes its shape.

The kinetic equation is used for the calculation of the distribution of impurities in the diffusion gradients of temperature and vacancies (1) [3].

\[
\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left( -D_A^{*}\frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( -D_B^{*}\frac{\partial C}{\partial y} \right) + \frac{C(1-C)C_v}{\kappa T^2} \left( E_A^{*}D_A^{*} - E_B^{*}D_B^{*} \right) \frac{\partial T}{\partial x}
\]

\[
- C(1-C)\left(D_A^{*} - D_B^{*}\right) \frac{\partial C_v}{\partial x} - C(1-C)\left(D_A^{*} - D_B^{*}\right) \frac{\partial C_v}{\partial y}
\]

Where, \( C \) - the concentration of atoms of type B, \( D_A^{*} = D_{0A}e^{-E_A^{*}/kT} \); \( D_B^{*} = D_{0B}e^{-E_B^{*}/kT} \) - self-diffusion coefficients of atoms of type A and B; \( D = (C_A^{*}D_A^{*} + C_B^{*}D_B^{*})C_v \) - the mutual diffusion coefficient \( E_A, E_B \) - the activation energy of the atoms A and B.

The first two terms describe the concentration diffusion, thermal diffusion process is third on the nonequilibrium vacancies. Such flow is directed in a direction opposite the temperature gradient, i.e. a movable component accumulates at the cold end of the sample. The fourth and fifth terms on the right-hand side describe the process of redistribution of elements caused by non-uniform thickness distribution of nonequilibrium vacancies. In this case, a movable component must accumulate on the
surface of the sample. There is the presence of competition and the effect of thermal diffusion process "vacancy wind": Equation (1) was solved by numerical methods, as analytically solve this equation is not possible. Calculations show that the titanium concentration increases at the surface of the sample (Figure 15).
Figure 15. Distribution of titanium steel 12X18H10T after electron beam irradiation. a) space distribution b) cross section in the x-axis, c) cross-section along the y axis.

The results of calculation are in good agreement with the experimental data. Figure 6 shows the results of measuring the distribution of the alloy components in depth. It is seen that the titanium concentration increases at the sample surface and at grain boundaries.

Figure 16. Distribution of the alloy components in the depth of the sample.
4. Conclusion

Electron beam irradiation of materials leads to abnormal redistribution of elements in alloys. That allows creating a predetermined impurity profile and providing the required performance of the product.

The experimental data shows that in the scope of the electron beam is formed thin films islet Ti. The film thickness must be less than 1.3 microns, as microanalysis shows the titanium’s content is of about 98%. If the film was thinner, microanalysis would show the content of other elements due to the "highlight" of the matrix.

The energy of electrons was quite low (less than 5 keV), consequently radiation defects were not formed and the entire beam energy went into heating of the target. The built-in modules of transient thermal and steady-state thermal temperature were found to be used numerically as the solution of the problem connecting with arbitrary geometry samples.

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