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# The life time of super 304H austenitic steel power boiler components under the unstable operation conditions

**J. Dobrzański*, A. Zieliński , H. Purzyńska**
[a] Institute for Ferrous Metallurgy, K. Miarki 12-14, 44-100 Gliwice, Poland
* Corresponding e-mail address: jdobrzanski@imz.pl

**ABSTRACT**

**Purpose:** The purpose of the work was to analyse the components of Super 304H (X10CrNiCuNb18-9-3) steel steam pipelines of power units after long-term service beyond the design work time.

**Design/methodology/approach:** The material for investigations included the 4th stage steam superheater coils, in the form of ø 42.4 x 8.8 mm pipes, made from Super 304H (X10CrNiCuNb18-9-3) steel, intended for operation under creep conditions at the design temperature 620°C and design pressure 28.5 MPa.

**Findings:** The effect of cyclic creep, and therefore shut-downs and repeated start-ups after long-term service under creep conditions beyond the design work time was determined.

**Research limitations/implications:**

**Practical implications:** The presented method can be used for evaluation and qualification of structural changes in power station boiler components operating under creep conditions.

**Originality/value:** The obtained results of investigations will be the elements of material characteristics developed by the Institute for Ferrous Metallurgy for steels made from them working under creep conditions.

**Keywords:** Creep; Steel Super 304H; Precipitation

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**PROPERTIES**

## 1. Introduction

Austenitic steels and nickel superalloys are used for construction of boilers with supercritical, i.e. temperature 565-620°C and pressure up to 30 MPa, and ultimately ultra-supercritical, i.e. 650-720°C and 30-35 MPa, steam parameters. The investigations of performance and development of this group of materials has become the key factor in design and construction of new power units [1-4]. It needs to be emphasised that this group of steels and alloys is used for critical elements, which include, but are not limited to, coils in the final stages of primary and secondary steam superheaters.

Austenitic steels for service at elevated temperature are characterised by better high-temperature creep and heat resistance than ferritic-based steels and are used for boiler components operating at above 600°C. The creep strength of metals is increased by substitution elements in the solution and stable particles from other phase. The rate of diffusion of substitution elements in austenite is approx. 100 times slower than in ferrite. In turn, a deficiency of austenitic steels is their high cost generated by high Ni content necessary for stabilisation of austenite, high coefficient of thermal expansion and low thermal conductivity, especially as the boiler tubes are heat exchangers.

The development of new-generation austenitic steel for use in boiler components with super- and ultra-supercritical steam parameters, which are the subject of research, is presented in Table 1.

Power units are not operated on a continuous basis. They are shut down and restarted from time to time The most often reasons for shut-downs may include the need to carry out planned repairs, no demand for electric energy or failures. Each subsequent shut-down and start-up affects the reduction in life time of all the system components working under creep conditions. The number of shut-downs during the 100,000 h design service life only, depending on the power unit, ranges between several dozens and several hundreds [5, 6].

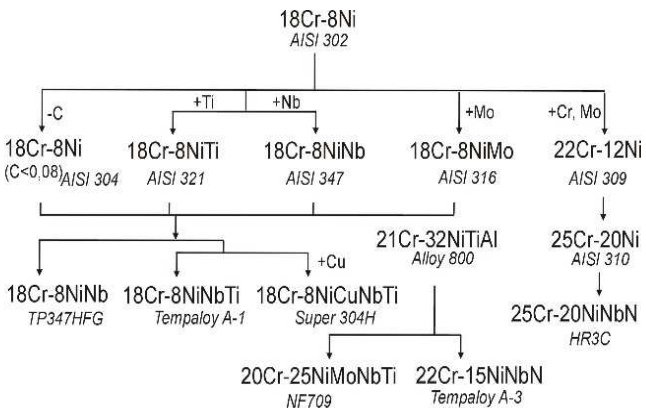


Fig. 1. Structure of P91 steel in the as-received condition

The creep causes permanent changes in the microstructure, resulting in decreased performance, in particular creep resistance. It results in reduction in the ability to transfer service loads of the material of components working under such conditions [5-12]. Material operated under such conditions shows lower and lower resistance to consecutive shut-downs and start-ups. At the same time, attention should be paid to the fact that the results of shut-downs and start-ups are not included in calculations. They are assumed to be within the safety factors adopted in design calculations [5].

To examine the effect of shut-downs and start-ups on the life time of material of components working under creep conditions, concurrently with the standard creep tests conducted at a constant temperature and constant stress the creep tests at a cyclically changed temperature and constant stress corresponding to that existing under the real working conditions are carried out [13-18].

Below, the selected creep and cyclic creep test results obtained for Super 304H (X10CrNiCuNb18-9-3) steel are presented and the nature of changes resulting in reduction in the life time are shown. The investigations on this steel to develop the characteristics of creep resistance, creep strength, creep limit and creep rate as well as changes in the microstructure, with particular consideration given to the course of precipitation processes, are conducted in many research centres [19-24].

## 2. Material for investigations

The material for investigations included the 4th stage steam superheater coils (from the outlet side), in the form of ø 42.4 x 8.8 mm pipes, made from Super 304H (X10CrNiCuNb18-9-3) steel, intended for operation under creep conditions at the design temperature To = 620°C and design pressure $p_o$ = 28.5 MPa. The material, in the form of coil sections, was taken during the manufacturing cycle of the Rafako Boiler Engineering Company in Poland (Fig. 2). Chemical composition of the material of examined Super 304H (X10CrNiCuNb18-9-3) steel pipes compared to the requirements in accordance with [25] is summarised in Table 1.

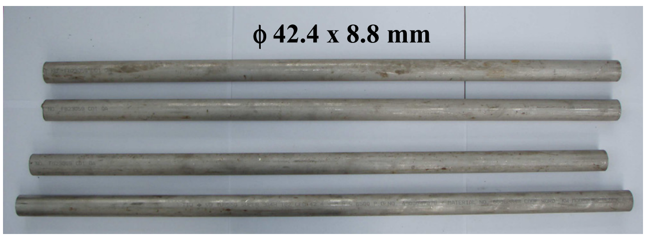


Fig. 2. Material for investigations in the form of the $4^{th}$ stage steam superheater coils from Super 304H (X10CrNiCuNb18-9-3) steel

Table 1.
Chemical composition of Super 304H (X10CrNiCuNb18-9-3) steel

| | Chemical composition [%] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | P | S | Cu | Cr | Ni | Nb | B | N | Al |
| Check analysis | 0.09 | 0.20 | 0.80 | 0.0032 | 0.000 | 2.99 | 18.4 | 8.8 | 0.48 | 0.004 | 0.11 | 0.0006 |
| ASME Code | 0.07 | max | max | max | max | 2.50 | 17.0 | 7.5 | 0.30 | 0.0001 | 0.05 | 0.0003 |
| Case 2328-1 | 0.13 | 0.30 | 1.00 | 0.0040 | 0.0010 | 3.50 | 19.0 | 10.5 | 0.60 | 0.0010 | 0.12 | 0.0030 |

## 3. Creep tests

The steam superheater coil material creep tests were carried out with elongation measurement and record during the test. These tests were carried out at the constant test temperature $T_b$ and at the constant stress $\sigma_b$. From the obtained test results, creep curves as a function of plastic strain ε and creep time t ($\varepsilon = f(t)$) were plotted. In addition, the life time defined as the time to rupture $t_r$ and the time at the end of stage II of the creep process $t_{II}$, which is called the disposable life time $t_b$ and is a part of the life time $t_r$, were determined based on these tests. This value is specific to each of the tested grades of material and needs to be determined separately.

At the same time, the cyclic creep tests were carried out alternately at $T_{b1}$ and at constant stress $\sigma_{b1}$, i.e. at parameters corresponding to those occurring under the real working conditions and after cooling to room temperature $T_{b2}$ = approx. 20°C and relieving the stress ($\sigma_{b2} = 0$). The method for conducting the creep tests and cyclic creep tests conducted at periodically changed temperature and stress parameters ($T_{b1}/T_{b2}$ and $\sigma_{b1}/\sigma_{b2}$) are shown graphically in Fig. 3. For cyclic creep tests, carried out at alternately changed test temperature from $T_{b1}$ = 650°C to $T_{b2}$ = 20°C, the holding time $t_1$ at $T_{b1}$ was always 336 h at the stress corresponding to the operating one $\sigma_{b1}$ = 200 MPa, and the total time $t_2$, including: cooling, holding at $T_{b2}$ and reheating to $T_{b1}$, with simultaneous stress relief, was always 24 h.

The time to rupture $t_r$ determined for cyclic creep tests conducted like those, which is the sum of component times of tests conducted at $T_{b1}$ under stress $\sigma_{b1}$, and the plastic strain $\varepsilon_t$ after the time t (Fig. 3b, c) were compared to the results of standard creep tests conducted at constant temperature $T_{b1}$ and constant stress $\sigma_{b1}$ (Fig. 3a).

The example of obtained creep and cyclic creep results for Super 304H steel for the adopted operating temperature $T_e$ = 650°C and test stress $\sigma_e$ = 200 MPa in the form of creep-to-rupture curves ($t_r$) are presented in Fig. 4.

The comparison of the time to rupture $t_r$ and the plastic strain $\varepsilon_t$, after the same creep duration of 3000 h, in the standard creep test ($T_b$ = 650˚C; $\sigma_b$ = 200 MPa) and the cyclic creep test ($T_b$ = 650/20˚C; $\sigma_b$ = 200/0 MPa), is summarised in Table 2. The time to destruction in both tests differs insignificantly and equals to 4391 and 4247 h, respectively. Also, the total permanent stress after rupture is similar and equals to approx. 22 %. And the plastic strain after 3000 h, i.e. before the end of the creep stage II, is different and equals to 4.2 and 5.8 %, respectively. The share of the creep stage II is lower for the cyclic creep test.

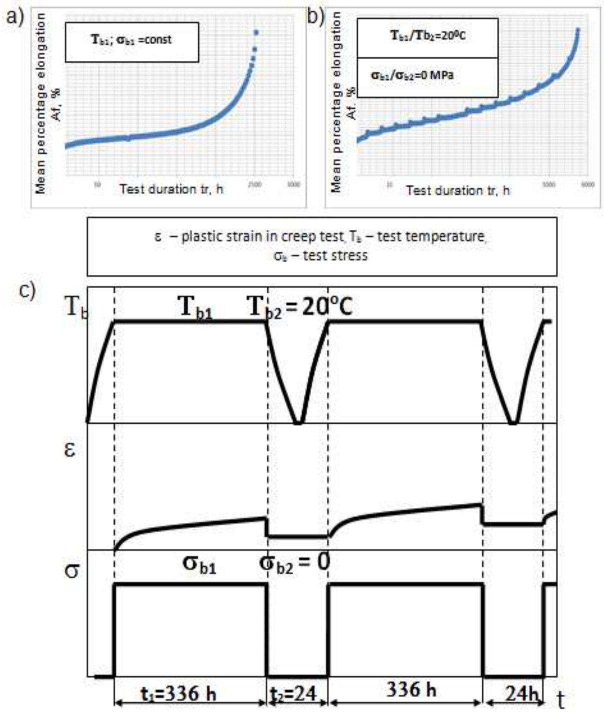


Fig. 3. Method for conducting creep tests: a) real standard creep curve for a test conducted at the constant test temperature and constant stress, b) real creep curve for a cyclic creep test conducted at cyclically changed temperature and with simultaneous stress relief, c) principles of cyclic changes in temperature $T_{b1}/T_{b2}$ with simultaneous relief of stress $\sigma_{b1}/\sigma_{b2}$ and recorded change in plastic strain ε in completed cyclic creep tests (Fig. 3b)

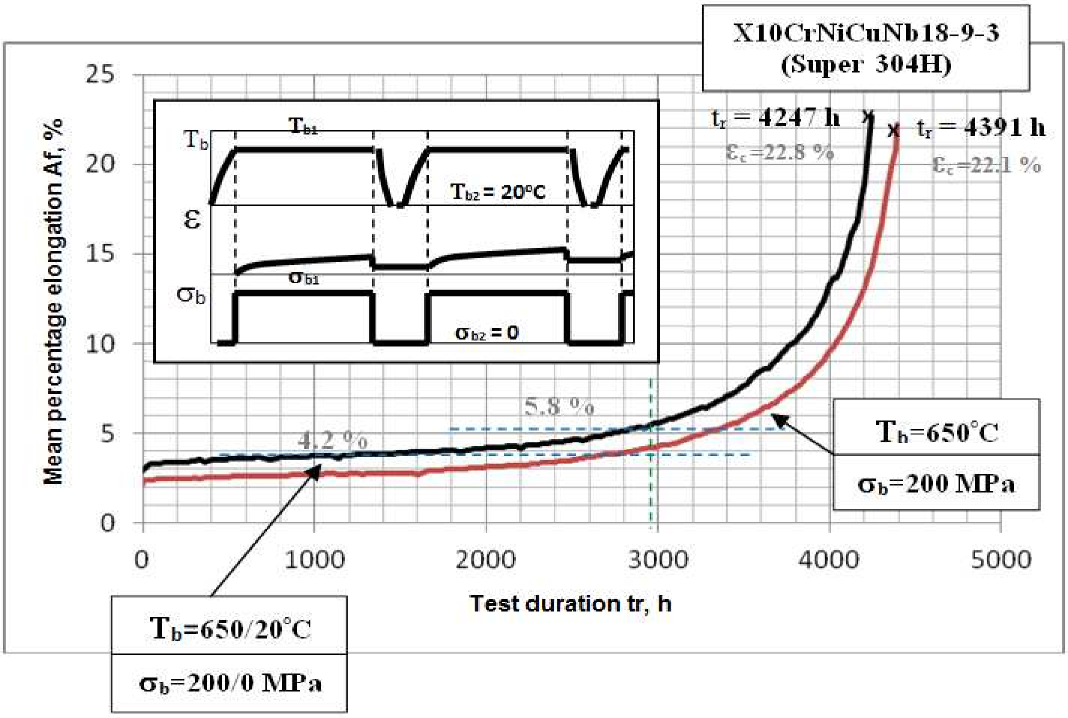


Fig. 4. Comparison of the results of creep tests conducted at cyclically changed test temperature $T_b$ = 650/20˚C and constant test stress $\sigma_b$ = 200/0 MPa with the standard creep test ($T_b$ = 650˚C; $\sigma_b$ = 100 MPa)

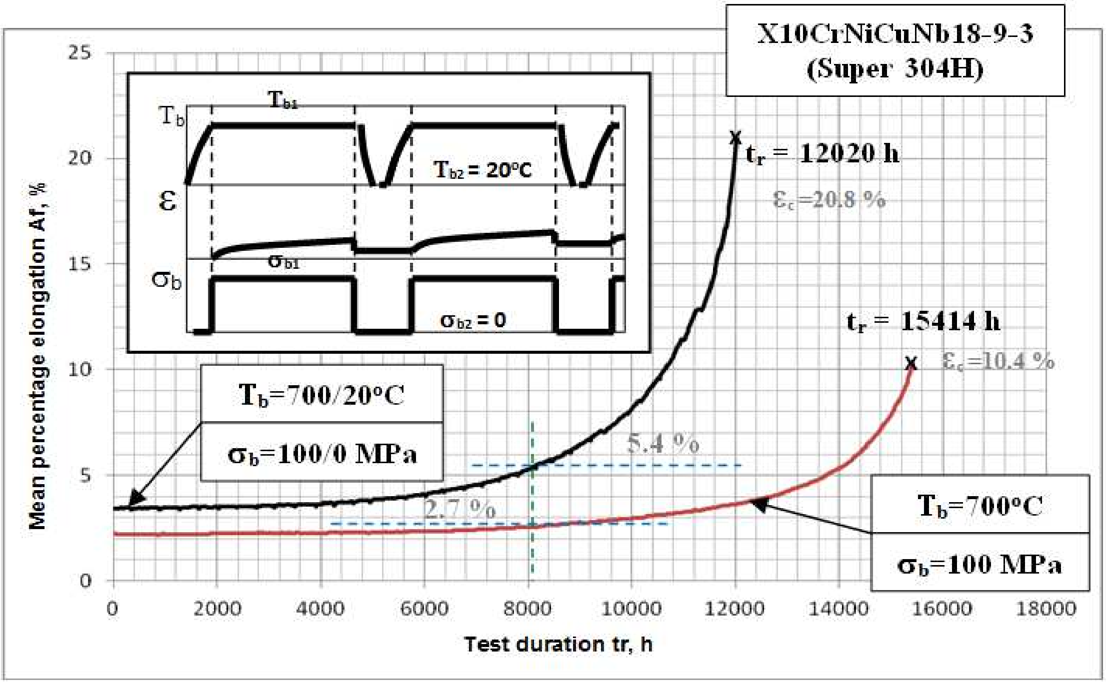


Fig. 5. Comparison of the results of creep tests conducted at cyclically changed test temperature $T_b$ = 700/20˚C and constant test stress $\sigma_b$ = 100/0 MPa with the standard creep test ($T_b$ = 700˚C; $\sigma_b$ = 100 MPa)

Table 2.
Comparison of time to rupture tr and plastic strain $\varepsilon_t$, after the same duration of t = 3000 h, in the standard creep test (Tb = 650°C; $\sigma_b$ = 200 MPa) and the cyclic creep test ($T_b$ = 650/20°C; $\sigma_b$ = 200/0 MPa) X10CrNiCuNb18-9-3 steel

| No. | Test type | Test parameters | | | | Duration of cycle components, h | | Time to rupture $t_r$, h | Plastic strain after t time, % | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Test temperature | | $t_{rbi}$ to L-M, h | | | | | | |
| | | $T_{b1}$, °C | $T_{b2}$, °C | $\sigma_{b1}$, MPa | $\sigma_{b2}$, MPa | for $T_{b1}$ | for $T_{b2}$ | | $\varepsilon_t$ for t = 3000 h | $\varepsilon_c$ for $t_r$ |
| 1 | Standard creep test | 650 | - | 200 | - | - | - | 4 391 | 4.2 | 22.1 |
| 2 | Cyclic creep test | 650 | 20 | 200 | 0 | 336 | 24 | 4 247 | 5.8 | 22.8 |

Table 3.
Comparison of time to rupture $t_r$ and plastic strain $\varepsilon_t$, after the same creep duration of t = 8000 h, in the standard creep test ($T_b$ = 700°C; $\sigma_b$ = 100 MPa) and the cyclic creep test ($T_b$ = 700/20°C; $\sigma_b$ = 100/0 MPa) X10CrNiCuNb18-9-3 steel

| No. | Test type | Test parameters | | | | Duration of cycle components, h | | Time to rupture $t_r$, h | Plastic strain after t time, % | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Test temperature | | $t_{rbi}$ to L-M, h | | | | | | |
| | | $T_{b1}$, °C | $T_{b2}$, °C | $\sigma_{b1}$, MPa | $\sigma_{b2}$, MPa | for $T_{b1}$ | for $T_{b2}$ | | $\varepsilon_t$ for t=8000 h | $\varepsilon_c$ for $t_r$ |
| 1 | Standard creep test | 700 | - | 100 | - | - | - | 12 020 | 2,7 | 10,4 |
| 2 | Cyclic creep test | 700 | 20 | 100 | 0 | 336 | 24 | 15 414 | 5,4 | 20,8 |

The comparison of the time to rupture $t_r$ and the plastic strain $\varepsilon_t$, after the same duration of 8000 h, in the standard creep test ($T_b$ = 700˚C; $\sigma_b$ = 100 MPa) and the cyclic creep test ($T_b$ = 700/20˚C; $\sigma_b$ = 100/0 MPa), is summarised in Table 3. The time to destruction in both tests differs insignificantly and equals to 15414 and 12020 h, respectively. Also, the total permanent stress after rupture differs twofold and equals to 10.4 and 20.8 %. The plastic strain after 8000 h, i.e. before the end of the creep stage II, is different and equals to 2.7 and 5.4 %, respectively. And the plastic strain at the end of the creep stage II for the standard creep test is approx. 3% and for the cyclic creep test, adopted conventionally, approx. 5.5 %. Also, the share of the creep stage II differs and is much lower for the cyclic creep test.

## 4. The effect of shut-downs and start-ups on the creep dynamics and life time

During long-term service of power unit components, numerous shut-downs and restarts are necessary. They result in creep stage I with each subsequent start-up in the materials of components working above the limit temperature where the predominating process is creep. This stage is characterised by significant increase in plastic strain over a short time.

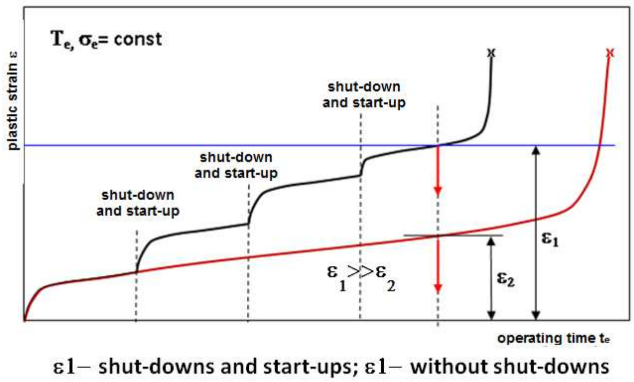


Fig. 6. Effect of shut-downs and start-ups on plastic strain due to creep

The consequence of the occurrence of creep stage I with consecutive start-ups is distinct increase in total plastic strain. Also, the result of consecutive start-ups is the reduction in total time to the end of creep stage II, and therefore the reduction in safe time of operation. The effect of consecutive start-ups on the plastic strain, with regard to the operation without shut-downs and start-ups, represented by standard creep curve as a function of plastic strain and creep time, under constant temperature and stress conditions, is shown in Figs. 6, 7.

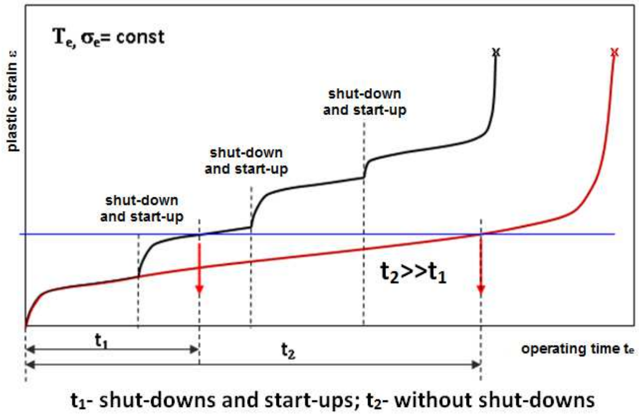


Fig. 7. Effect of shut-downs and start-ups on the time of reaching the same plastic strain

The creep tests at the cyclically changed temperature ($T_{b1}/T_{b2}$ = 20°C) and at constant stress ($\sigma_{b1}/\sigma_{b2}$ = 0) allowed the effect of shut-downs and consecutive start-ups on the life time of the material of components working under creep conditions to be determined. The time to rupture tr, and therefore the life time, may be even a few times lower for the cyclic creep tests. Differences in these values are not constant and depend on the grade of steel, and therefore its microstructure, and on the temperature and stress parameters of tests. The plastic strain $\varepsilon_t$ in the cyclic creep tests after the same total test duration may be higher by even more than 100% compared to that obtained in the standard creep test conducted at the same temperature and at the same stress level.

## 4. Summary

Creep tests at the cyclically changed temperature and at constant stress corresponding to that existing under the real service conditions allowed the effect of shut-downs and consecutive start-ups on the life time of material of the 4$^{th}$ stage steam superheater coils made of Super 304H austenitic steel, working under creep conditions, to be determined.

The plastic strain $\varepsilon_t$ in the cyclic creep tests after the same total test duration may be higher, by even more than 100%, compared to that obtained in the standard creep test conducted at the same temperature and at the same stress level. And the time to rupture $t_r$, and therefore the life time, may be even a few times lower for the cyclic creep tests. Differences in these values depend on the grade of steel, and therefore its microstructure, and on the temperature and stress parameters of tests.

The effect of cyclic creep, and therefore shut-downs and repeated start-ups, particularly from a cold start, is definitely higher for lower stress levels and higher temperature, and their results will be clear after long-term service. It can be attributed to differences in creep nature and dynamics resulting in degradation of microstructure and reduction in the material's ability to transfer the real service loads. At the time when the share of thermally activated creep-related processes is predominating (relatively low stress level and operating temperature similar to the limit one for the grade of material after long-term service), the highest reduction in the life time should be expected.

## Acknowledgements

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## Additional information

Selected issues related to this paper are planned to be presented at the 22$^{nd}$ Winter International Scientific Conference on Achievements in Mechanical and Materials Engineering Winter-AMME'2015 in the framework of the Bidisciplinary Occasional Scientific Session BOSS'2015 celebrating the 10$^{th}$ anniversary of the foundation of the Association of Computational Materials Science and Surface Engineering and the World Academy of Materials and Manufacturing Engineering and of the foundation of the Worldwide Journal of Achievements in Materials and Manufacturing Engineering.

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