Building low-cycle fatigue curve to assess remaining lifetime of steel-teeming ladle turret

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Abstract. The tests were performed for low-cycle fatigue at the temperature of 90^{0}C on the 15ХСНД steel samples, which were taken from a lifting beam of CCM turret No.6 of PJSC Magnitogorsk Iron & Steel Works (MMK). The tests were performed using the Gleeble 3800 thermomechanical simulator in air atmosphere. The measurements of the sample deformations in the course of the testing were performed using a high-temperature detector of lateral deformations. According to the test results, fatigue curves were built for stress and deformation conditions, as well as a cycle curve of deformation. Regression equations were obtained for the low-cycle fatigue curve for stress and deformation conditions, as well as the regression equation for the cycle curve of deformation. It was demonstrated that the experimental values of stress and deformation conditions fit into the confidence interval of these equations with a probability of 99.5%, which allows using them for the assessment of the remaining lifetime of cyclically loaded structures of CCM ladle turret No.6.

1. Introduction

A continuous casting machine (CCM) includes a ladle turret, which consists of a base, a rotating platform, and a cross head with hangers. The ladle turret is intended for receiving a steel-teeming ladle with metal into a standby position, and moving it from the standby position to teeming position and back [1,2]. During metal teeming the ladle turret provides for fulfillment of the operations of lifting, lowering and continuous weighing of the ladle.

The ladle turret is a heavy-loaded welded structure pertaining to the category of dangerous technical equipment, taking up significant static, cyclic and temperature impacts leading to its performance degradation [3-6].

It is worth noting that during reconstruction and upgrade of the ladle turret the cyclic character of external impacts is not always being taken into account, while the amplitude of their variation may lead to failure of the most loaded elements [7-9].

In this work tests on the low-cycle fatigue were performed for 15ХСНД steel samples taken from a lifting beam of CCM turret No.6 of PJSC Magnitogorsk Iron & Steel Works (MMK) in order to assess the remaining lifetime and make a decision on the ladle turret upgrade.

2. Research Methods and Results

2.1. Testing method

The low-cycle fatigue tests were performed in compliance with [10,11] on double cylindrical test-pieces with the diameter of 6 mm (Figure 1).The chemical composition and mechanical properties of the samples material at the temperature of 20^{0}C are given in Tables 1,2.

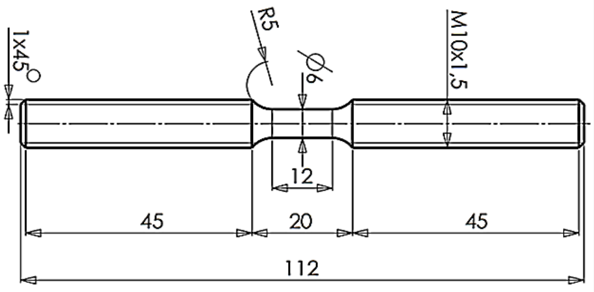

Figure 1. Sample for testing on the low-cycle fatigue.

Table 1. Chemical Composition of 15XCНД Steel.

Chemical Elements Content, %							
C	Mn	Si	Cr	Ni	Cu	S	P
0.14	0.57	0.40	0.64	0.40	0.27	0.016	0.012

Table 2. Mechanical Properties of 15 HSND Steel.

No.	σ_m, MPa	σ_b, MPa	δ_5, %	ψ, %	KCU^{+20}, J/cm^2
1	410	544	34	72	256
2	424	568	38	78	269

Note: The tests were performed for quintuple samples at the temperature of 20^{0}C according to GOST 1497-84 [12].

The tests on the low-cycle fatigue were performed using Gleeble 3800 thermomechanical simulator, in which samples are heated by passing electric current through them. The heating temperature equaled 90^{0}C and was controlled by a chromel-alumel thermocouple. To measure deformation, a high-temperature detector of lateral deformation (hereinafter referred to as the dilatometer) was used.

The tests were sequenced as follows. First, during single tension till destruction two samples were tested (see Fig. 1), and deformation and mechanical characteristics of steel at the temperature of 90^{0}C were determined. The average values of the testing results are given in Table 3.

Table 3. Mechanical Properties of 15 HSND Steel.

σ_b, MPa	ψ, %	E, GPa	μ
510	70	205±10	0.3

Note: The tension tests were performed for double samples at the temperature of 90^{0}C.

After that the values of logarithmic deformations were calculated using the following formula [10]:

$$\varepsilon = \varepsilon_G + \left(1 - 2\mu\right)\sigma / E, \quad (1)$$

where E is the modulus of elasticity for tension equaling 2.05·10^6 MPa; μ is the Poisson's ratio assumed to equal 0.3; ε_G is the value of logarithmic deformation computed by Gleeble 3800 complex software using the following formula [13]:

$$\varepsilon_G = 2\ln\left[d_0 / \left(d_0 + \Delta d\right)\right]. \quad (2)$$

here d_0 is the sample's initial diameter; Δd is the variation of the sample's diameter measured in the course of testing (readings of the dilatometer).

On the grounds of the obtained results the levels of deformation ranges $\Delta\varepsilon_G$ were set, and the low-cycle testing of the samples was performed in compliance with GOST 25.505-85.

According to the results of the tests on the first samples, the set levels of deformation were corrected in order to obtain the points of the fatigue curve within the range of $10 \div 10^5$ of cycles till destruction. The fatigue curve was built through interpolation of the experimental points using the least squares method.

The rate of deformation at static and cyclic impact was constant and equaled 0.01 s^{-1}. All the tests were performed in air atmosphere at the temperature of 90^0C.

The preliminary assessment of the levels of deformation range Δ was bsed on the method of multipurpose tilting [14] using the empirical dependencies of Manson [15]

$$\Delta\varepsilon = 3.5\left(\sigma_b / E\right) N^{-0.12} + \ln^{0.6}\left[1/\left(1-\psi\right)\right] N^{-0.6} \quad (3)$$

and of Manson-Muralidharan [16]

$$\Delta\varepsilon = 1.17\left(\sigma_b / E\right)^{0.832} N^{-0.09} + 0.0266 \ln^{0.155}\left[1/\left(1-\psi\right)\right]\left(\sigma_b / E\right)^{-0.53} N^{-0.56}, \quad (4)$$

where N is the number of destruction cycles.

As source data for calculation the values of σ_b and ψ given in Table 3 were assumed. The preliminary assessments of the deformation ranges corresponding to the numbers of cycles till destruction 10, 100, 1000, 10000 and 100000 are given in Table 4 and on Figure 2.

Table 4. Preliminary Assessment of the Levels of Deformation Range.

N	0.5	10	100	1000	10000	100000
$\Delta\varepsilon$	$\ln[1/(1-\psi)]$	0.25	0.07	0.02	0.007	0.0035

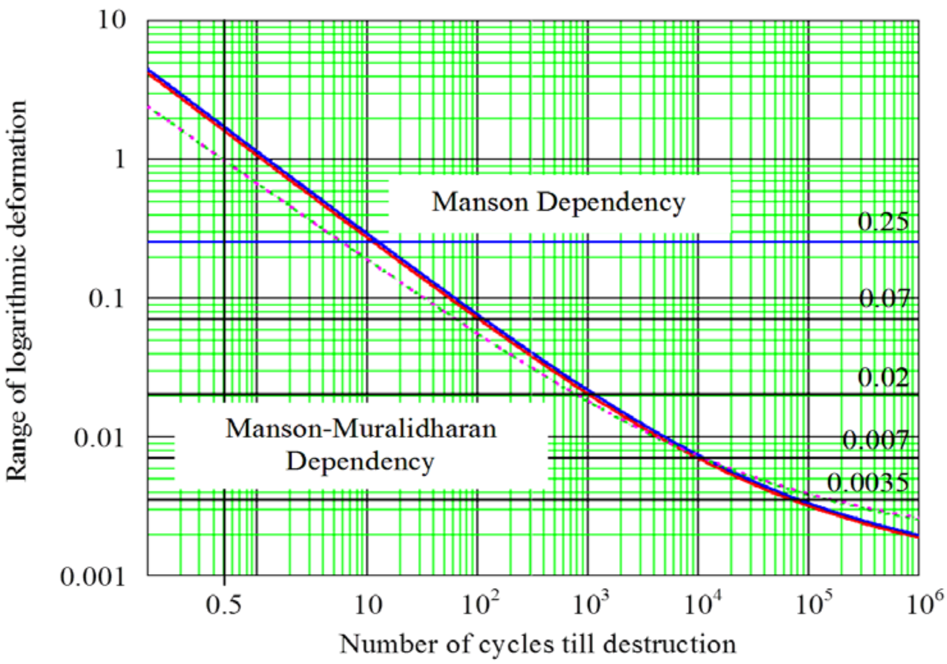

Figure 2. Assessment of the levels of the logarithmic deformation range.

2.2. Results of cyclic tests

The tests on low-cycle fatigue were performed starting from the highest levels of the deformation range. As the test results were being obtained, the levels of the deformation range were corrected to obtain the number of cycles till destruction close to the values set earlier: 10^2, 10^3, 10^4 and 10^5. As a planned stop of testing the sample's destruction was assumed or a significant (more than 50%) decrease in the stress range as compared to an established one.

During determining the deformation range $\Delta\varepsilon$ the dependency of type (5) was used, which takes into account the error of deformation determining by Gleeble 3800 test unit's software:

$$\Delta\varepsilon = \Delta\varepsilon_G + (1-2\mu)\Delta\sigma / E, \quad (5)$$

where $\Delta\varepsilon_G$ is the deformation range as per detector; $\Delta\sigma$ is the stress range.

The test results at the selected values of the deformation ranges are given in Table 5.

Table 5. Results of Tests in Low-cycle Fatigue

No. per item	Deformation Range $\Delta\varepsilon_G$	Deformation Range $\Delta\varepsilon$	Stress Range $\Delta\sigma$, MPa	Number of Cycles till Destruction N
1	0.070	0.0722	1134	20*
2	0.054	0.0561	1090	88
3	0.05	0.0521	1080	66
4	0.0196	0.0214	910	418
5	0.0195	0.0213	927	567
6	0.008	0.00952	777	2545
7	0.008	0.00948	759	2902
8	0.0043	0.0057	700	7681
9	0.004	0.00534	685	8890
10	0.00275	0.00408	684	10379
11	0.0024	0.00369	661	11796
12	0.00245	0.00384	650	15348
13	0.00199	0.00319	614	17330

* The sample had lost stability before destruction occurred.

2.3. Building of the Fatigue Curve

According to the testing results given in Table 5, a fatigue curve for stress was built (Figure 3).

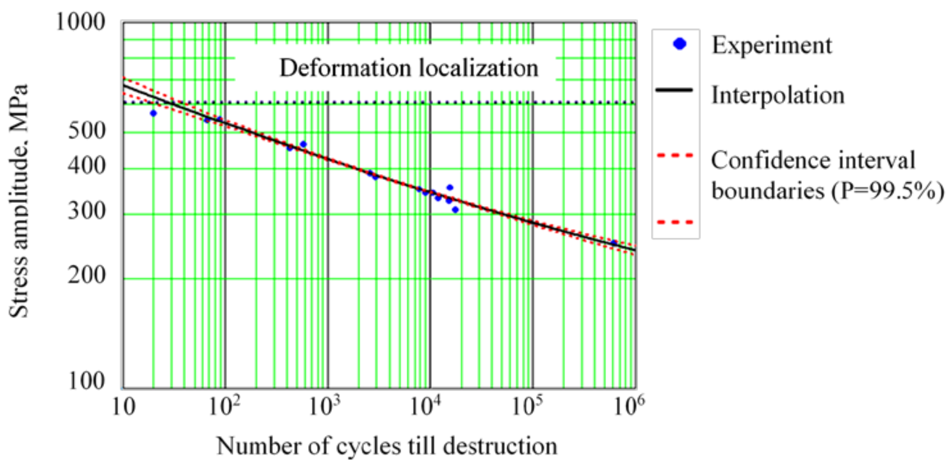

Figure 3. Fatigue curve for stress.

To interpolate the experimental data, a regression equation of the following type was used [17]

$$\Delta\sigma / 2 = \sigma_{-1} + GN^{\gamma} \quad (6)$$

where σ_{-1} = 105 MPa, G = 756 MPa, γ = –0.126 are the values of parameters obtained through the least squares method.

The boundaries of the confidence interval (with a probability of 99.5%) for the regression equation were assessed according to [18,19].

Also, directly according to data of Table 4, a cycle curve of deformation was built [20] – the dependency of the stress amplitudes on the deformation amplitudes after cyclic stabilization (Figure 4).

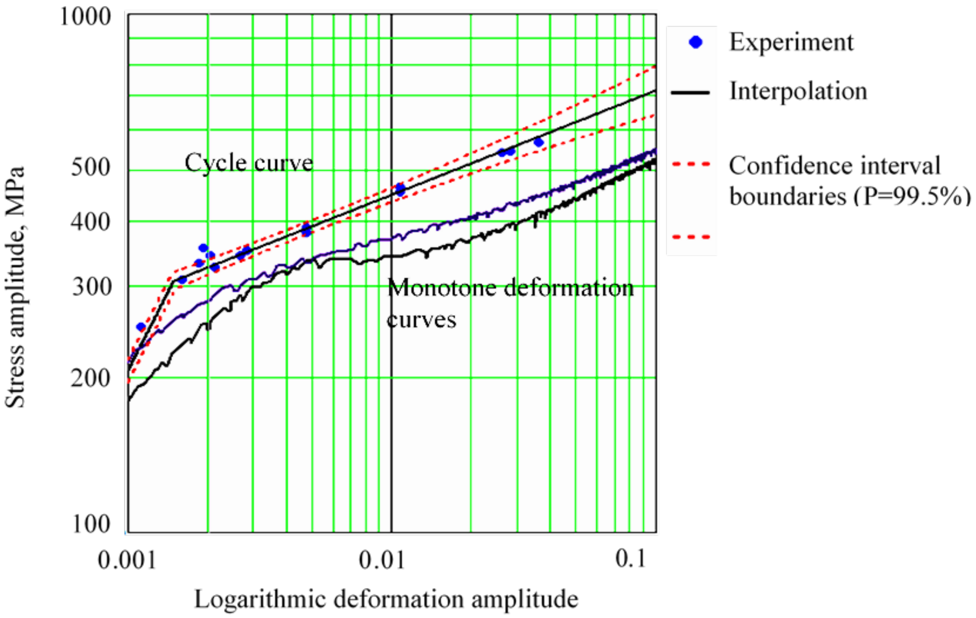

Figure 4. Cycle curve of deformation.

The regression equation looks as follows:

$$\Delta\sigma / 2 = \min\left[E\,\Delta\varepsilon / 2; K\left(\Delta\varepsilon / 2\right)^{m}\right], \quad (7)$$

where K = 1131 MPa, m = 0.201 are the values of parameters obtained using least squares method; $\Delta\sigma/2 = E\,\Delta\varepsilon/2$ is the equation in case of elastic deformation; $\Delta\sigma/2 = K(\Delta\varepsilon/2)^m$ is the equation in case of elasto-plastic deformation.

The boundaries of the confidence interval (with a probability of 99.5%) for the power section of the regression equation were assessed according to [18,19], and for the elastic area – based on the error of determining the value of the modulus of elasticity within the range of 205±10 GPa.

During solving the equation (9) related to the range of logarithmic deformation, the fatigue curve equation for deformation was obtained (Figure 5):

$$\Delta\varepsilon = 2\max\left\{\left(\sigma_{-1} + GN^{\gamma}\right) / E; \left[\left(\sigma_{-1} + GN^{\gamma}\right) / K\right]^{1/m}\right\} \quad (8)$$

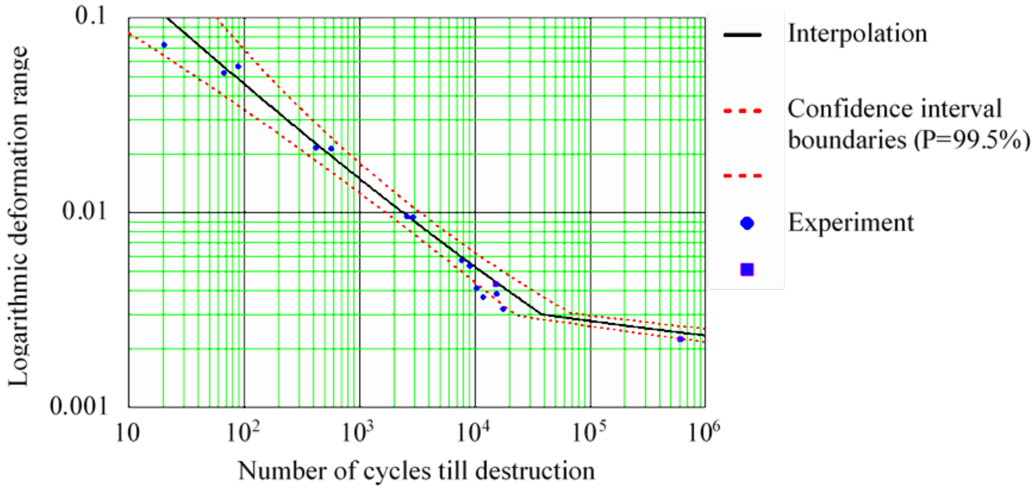

Figure 5. Fatigue curve for deformation.

3. Conclusion

1. According to the results of testing 15ХСНД steel samples, fatigue curves for stress and deformation were built, as well as a the cycle curve of deformation – a dependency of stress amplitudes on deformation amplitudes after cyclic stabilization.
2. Regression equations were obtained for low-cycle fatigue curve for stress (6) and deformation (8) for 15HSND steel, as well as the regression equation for the cycle curve of deformation (7).
3. The experimental values of stress and deformation with a probability of 99.5% fit within the boundaries of the confidence interval of these equations. This allows to use the obtained equations for assessment of the remaining lifetime of cyclically loaded structures of CCM ladle turret No.6.

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