Effect of forming on automotive sheet steel performance properties

G.V. Pachurin[1], *N.A.* Kuzmin[1], *M.V.* Mochalina[2*], *A.A.* Fillipov[1], *Z.V.* Smirnova[2], and *L.I.* Kutepova[2]

[1]Nizhny Novgorod State Technical University named after R.A. Alekseev, Minin Street, 24, 603950, Nizhny Novgorod, Russia
[2]Minin Nizhny Novgorod State Pedagogical University, Chelyuskintsev street, 9, 603138, Nizhny Novgorod, Russia

Abstract. In all industry sectors and in the automotive industry, in particular, structural materials that undergo various treatment methods are widely used. Various types of plastic deformation are widely used in the manufacture of products and structural elements made of low-carbon sheet steels. The authors studied the effect of the degree of technological deformation on the fatigue process parameters of flat low-carbon steels. It has been established that the preliminary deformation within the uniform limits causes an increase in fatigue resistance. The kinetic diagrams of the fatigue failure are used to estimate the change in durability from the rate of accumulation of fatigue damage at the cyclic deformation stage until the moment of origination and propagation of the fatigue crack. The ratio of the duration of fatigue failure stages of some sheet automotive steels depending on the degree of preliminary strain by stretching at a given amplitude stress of the cycle is revealed.

1 Introduction

The development of the economy requires a constant growth in industrial production, the emergence of new industries, an increase of the material, energetic, informational potential of industrial complexes and systems. To achieve this task, fairly new and science-intensive, environmentally friendly, material- and energy-saving, resource-saving technologies are used and associated with the penetration of scientific and technological progress into technical devices and technological processes [1,2].

It is especially important to note the need to create conditions for the safe functioning of machines and mechanisms when interacting with a person. Safe and at the same time effective use of technical devices in the process of implementing various types of human life creates optimal conditions for improving its performance, provides the possibility of implementing recreational resources for a good rest. There are many known cases of harm to human health due to accidents provoked by damage or destruction of technical devices used in production or other conditions, deviation from the technological process, as a result of failure of critical parts. The search for solutions to the problems of the safe use of technical

* Corresponding author: mariyamuhina@yandex.ru

means ensures the preservation of human life and health by reducing injuries and the risk of morbidity.

Therefore, the most important link in this chain is to increase the reliability, technical level and quality of manufactured products by improving the operational and technological properties of industrial products. The constant increase in the requirements for the quality of products, assemblies, structures, materials leads to the need to deeply and in detail study the conditions in which they function.

Thus, the issue of increasing the reliability and safe operation of machine parts and technical devices is the most important problem of all branches of industry and modern science [3,4]. Most of the critical parts and elements of equipment and machines are operated under the influence of vibration loads [5-7]. This involves the search for design and technological solutions that guarantee the required performance characteristics of both parts and machines as a whole [8–10].

Structural materials undergoing various treatment methods are widely used in all industry sectors [11-13]. Various types of plastic deformation are widely used in the manufacture of products and structural elements made of low-carbon sheet steels [14-16]. In particular, during cold forming with deep and complex drawing, various elements of the product experience stretching deformation of varying degrees.

It is known [17, 18, 21] that technological strengthening on the fatigue resistance of structural materials has an ambiguous effect, which leads to incomplete exhaustion of their safety margin during operation [19].

The paper presents the results of studies of the low-carbon sheet steel fatigue failure parameters depending on the degree of preliminary deformation by stretching (ε_{pd}).

2 Testing method

To solve this issue, low-carbon cold-rolled sheet steel grade 08kp, 08YU, hot-rolled steel grade 08YUA, 07GSUFT, 08GSIUT and 07GBY, widely used in automotive and other industry sectors, were selected after various degrees of preliminary plastic deformation.

Technological deformation of 0 ... 29% of the samples was carried out at the room temperature by stretching on the "INSTRON" with a strain rate of 2 10^{-3} s^{-1} and upsetting in a press through a lining tool with a deformation rate of $10^{-1}s^{-1}$. In this case, not the entire sample was subjected to upsetting, but only a part of it in a critical cross-section.

Plates with cross-sectional dimensions of 3×20 mm were subjected to preliminary plastic deformation, from which the samples were made both for static tensile tests (with a cross-section of 3×3 mm, subject to the ratio $l_0=11.3\sqrt{A_0}$ being between the initial design length of the sample l_0 and the cross-sectional area A_0) and for fatigue tests (dimensions of the working part corresponded to Type IV of flat samples [19]).

Fatigue tests were carried out according to the scheme of soft loading by alternating cyclic bending at the unit that allows recording changes in the sample deflection during loading [19].

3 Test results and discussions

Fatigue curves in double logarithmic coordinates are given in Table. 1. Their equations are:

$$\lg\sigma = \lg\sigma_0 - \beta \lg N,$$

Where β is the tangent of the fatigue curve inclination angle, which characterizes the ability of the material to resist cyclic loading.

In table. 1 shows the parameters of the equations of these fatigue curves.

Steel 08kp in the cold-rolled state has a limited endurance limit in the air 1.9 and 1.7 times higher than that of hot-rolled steels 07GSYuFT and 08GSUT, respectively (base 10^6 cycles).

Table 1. Fatigue curve equations for steel grade 08kp, 08U, 08UA, 07GSUFT and 08GSUT.

Item No.	Steel grade	Pre-deformation		$\lg \sigma = - \mathrm{tg}\, \alpha_\omega \lg N + \lg \sigma_a$ or $Y = - A X + B$
		scheme	rate. %	
1	2	3	4	6
1	08kp	-	Cold-rolled	Y = – 0.088 X +3.024
2	08 kp	upsetting	5	Y = – 0.999 X + 3.066
3	08 kp	upsetting	17	Y = – 0.085 X + 3.005
4	08 kp	upsetting	29	Y = – 0.083 X + 2.980
5	08U	—	Cold-rolled	Y = – 0.132 X + 2.921
6	08U	upsetting	12	Y = – 0.134 X + 2.910
7	08UA	-	Hot-rolled	Y = – 0.121 X + 3.163
8	08UA	stretching	2.5	Y = – 0.194 X + 3.484
9	08UA	stretching	5	Y = – 0.204 X + 3.582
10	08UA	stretching	10	Y = – 0.291 X + 4.157
11	08UA	stretching	15	Y = – 0.339 X + 4.364
12	08UA	stretching	20	Y = – 0.416 X + 4.812
13	08GSUT	upsetting	Hot-rolled	Y = – 0.096 X + 2.933
14	08GSUT	upsetting	5	Y = – 0.067 X + 2.812
15	08GSUT	upsetting	17	Y = – 0.089 X + 2.925
16	08GSUT	upsetting	29	Y = – 0.090 X + 2.943
77	07GSUFT	upsetting	Hot-rolled	Y = – 0.161 X + 3.258
18	07GSUFT	upsetting	5	Y = – 0.150 X + 3.240
19	07GSUFT	upsetting	17	Y = – 0.142 X + 3.207
20	07GSUFT	upsetting	29	Y = – 0.109 X + 3.067

Technological deformation by 29% reduces by 1.05 for steel 08kp and by 1.3 and 1.1 times the limited endurance limit on the same base for steels 07GSYuFT and 08GSUT, respectively, but for steel 08kp, it remains 1.2 times higher than that of the low-alloy steels. Although these steels have higher strength and yield strength values than 08kp steel, they have lower fatigue resistance (based on 106 cycles) – 1.6 and 1.4 times, respectively. Thus, steel 08kp shows more stable and superior parameters of fatigue failure resistance than steel grade 07GSUFT and 08GSUT.

The structure of 08kp steel consists of ferrite with a small amount of perlite, and the nature of fatigue failure of samples tested in air is mainly viscous. Low-alloy steel grade 07GSUFT and 08GSUT have carbide inclusions [11], which prevent the movement of dislocations and lead to an increase in strength properties under static tension. However, carbide inclusions are also the sources of micro-cracks during stretching, which negatively affect the plasticity parameters. Under the effect of cyclic loads, these cracks activate the development of fatigue failure processes and initiate longitudinal cracking of samples, and, consequently, contribute to a loss of their durability. Therefore, regardless of the pre-treatment modes, the samples made of 08kp steel have a higher fatigue resistance than low-alloy steel grade 07GSUFT and 08GSUT [19].

Cold-rolled steel grade 08U preliminary deformation by upsetting by 12% at high stress, for example, at σ_a = 250 MPa, reduces service life by 1.37 times. Low stress levels (for example, at σ_a = 150 MPa) reduce the durability of cold-rolled steel deformed by 12% by 1.42 times.

It has been established that the increase in tensile strain of steel 08YuA has an ambiguous effect on the fatigue limit σ_{-1} based on tests of N = 107 cycles.

So pre-stretching to ε_{pd} = 2.5% leads to a decrease in the fatigue limit by 15%, compared with undeformed samples. This may be due to the appearance of metal destruction in the most weakened grains, internal residual stresses, and inhomogeneity of plastic deformation. With a subsequent increase in technological deformation, σ_{-1} increases to a maximum σ_{-1} = 197 MPa at ε_{fd} = 15%, however, without exceeding the fatigue limit of the original samples σ_{-1} = 200 MPa.

With an increase in εd, the deformation ability of technologically processed samples deteriorates, and, with a decrease in the amplitude stress of the cycle σ_a, the intensity of accumulation of destructive damage increases

The parameters of the fatigue curve equations are provided in Table 2, where r is the correlation coefficient.

Table 2. The parameters of the fatigue curve equations (hot-rolled steel 07GBU at the 1st stage).

No.	ε_{pd} .%	Parameters of equation of curve ε_{pd} =f(N_1) at σ_a=300 MPa			Fatigue curve equation parameters		
		r	C	$\lg\varepsilon_0$	r	β	$\lg\sigma_0$
1	0	-0.96	-0.0117	0.032	-0.95	0.106	3.078
2	2.5	-0.95	0.0235	-0.087	-0.93	0.186	3.474
3	5	-0.97	0.0169	-0.062	-0.91	0.257	3.869
4	10	-0.98	0.0122	-0.046	-0.94	0.288	4.073
5	14	-0.95	0.00645	-0.022	-0.93	0.291	4.108
6	17	-0.97	0.0079	-0.031	-0.92	0.349	4.395

As a result of fatigue tests, it was established (Table. 2) that the dependences of the change in the index β and the fatigue limit σ_{-1} based on N = 10^7 cycles tests on the ε_{pd} preliminary deformation extent can be divided into three sections:

- section one: ε_{pd} = 0-5 %;
- section two: ε_{pd} = 5-14 % and
- section three: ε_{pd} > 14%.

In the first section, there is a sharp increase in the β index, the value of which, β = 0.257 at ε_{pd} = 5%, is 2.4 times higher than that of the undeformed samples, and a decrease in the fatigue limit to a minimum σ_{-1} = 200 MPa at ε_{pd} = 2.5% (compared with the undeformed samples σ_{-1} decreases by 15%), which may be due to the occurrence of damage in the weakest surface grains of the metal, with the nature and level of internal residual stresses, the degree of heterogeneity of plastic deformation [11].

In the second section, the growth of the β indicator slows down significantly (at ε_{pd} = 14 % β = 0.291, that is, 13% more than in samples deformed at ε_{pd} = 5%), and the fatigue limit continuously increases and at ε_{pd} = 14% reaches a maximum σ_{-1} =230 MPa, which corresponds to the fatigue limit of the undeformed samples.

Deterioration of fatigue characteristics in the third section (decrease in σ_{-1} value to 216 MPa and a further increase in indicator β to 0.349 at ε_{pd} = 17%) cause deterioration of fatigue characteristics in the third section, which is obviously caused by the occurrence of a defective structure during plastic deformation by stretching, when submicroscopic cracks arise in local volumes of metal with a critical dislocation density, which under a cyclic loading initiate the development of micro-plastic deformations and reduce the resistance to the origination and propagation of fatigue cracks [12].

Additional information about the accumulation of cyclic damage can be obtained by considering the change in the bending deflection (ε_{bd}) of the sample:

$$\varepsilon_{bd} = \frac{f_i}{f_0}$$

 https://doi.org/10.1051/e3sconf/202340211008

Where f_0, f_i are, respectively, the values of the initial and current bending deflection of the sample in the function N of the loading cycles number.

Previously [20], we obtained similar experimental data for hot-rolled steel grade 08U and 08UA pre-deformed by stretching. It is established that the fatigue fracture process can be divided into two stages: stage N_1 (until the moment of origination and propagation of the fatigue crack), which corresponds to a flat section of the curve $\varepsilon_{bd} = f(N)$, and stage N_2 of the propagation of the fatigue crack (from the moment of crack origination to its complete propagation along the sample section), which corresponds to a steep section of the curve $\varepsilon_{bd} = f(N)$.

The number of cycles N before failure is usually determined by the index C, which evaluates the rate of fatigue failure at the first stage of fatigue failure. Its value is determined from the equation $\lg \varepsilon_{bd} = \lg \varepsilon_0 \pm C \lg N_1$ [12].

The dependence of the parameters of this equation on the degree of technological deformation εp.d. are summarized in Table 2.

The analysis of the results shows that the prevailing process during cyclic loading of the undeformed samples is cyclic hardening ($\varepsilon_{bd} <1$), the indicator C = - 0.0117; N=3.45 •10^5 cycles.

Preliminary plastic deformation leads to a change in the mechanism controlling the rate of the fatigue process, since hardening is replaced by softening (ε_{bd}.>1). At the same time, it should be noted that the capacity of the hardened structure to cyclic softening is satisfactory when the ratio $\frac{\sigma_v}{\sigma_{0,2}} < 1.2$ is fulfilled.

Durability at ε_{pd} = 2.5% is reduced to N = 2 • 10^5 cycles at a value of C = 0.0235. A further increase in the ε_{pd} from 5 to 14% reduces the C index, which corresponds to an increase in the durability of pre-deformed samples. So, for ε_{pd} = 5% (C = 0.0169), N =2.4 • 10^5 cycles, and for ε_{pd} = 14% (C = 0.00645), N= 3.5• 10^5 cycles.

At the same time, the duration of the first stage of the fatigue damage accumulation process for the undeformed samples is N_1 = 2.25•10^5 cycles, which in relation to the total number of cycles before destruction N; is $\frac{N_1}{N} = 0{,}65$ at ε_{pd} = 2.5% the ratio $\frac{N_1}{N} = 0{,}47$; at ε_{pd} = 5-17% the ratio $\frac{N_1}{N}$ is within 0.45-0.3 limits. This means that technological tension causes a monotonous reduction in the first stage of fatigue failure. The cyclic life of technologically deformed samples is controlled by the stage of subsequent growth of a fatigue crack from the moment of its appearance.

4 Conclusions

1. The effect of preliminary technological deformation on cyclic durability and limited endurance limit is non-monotonous and is controlled by stress. The greatest increase in the fatigue resistance of a pre-deformed structural material is observed within the limits of uniform plastic deformation
2. Fatigue curves have been obtained for low-carbon cold-rolled sheet steel grade 08kp, 08U, and hot-rolled steel grade 08UA, 07GSUFT, 08GSUT and 07GBU widely used in automotive and other industries after various degrees of preliminary plastic process deformation.
3. According to the kinetic diagrams of fatigue failure, an assessment of the change in durability from the rate of accumulation of fatigue damage at the stage of cyclic deformation to the moment of origination and propagation of the fatigue crack is provided.
4. The ratio of the duration of fatigue failure stages is established depending on the degree of pre-deformation by stretching at a given amplitude stress of the cycle.

References

1. V.F. Terentyev, *Fatigue of high–strength metal materials* (IMET RAS - CIAM, Moscow, 2013)
2. G.V. Pachurin, S.M. Shevchenko, A.A. Filippov, et al., Materials Science and Engineering **327(3)**, 032040 (2018) DOI: https://www.researchgate.net/publication/329726335
3. V.F. Terentyev, S.A. Korablev, *Fatigue of metals* (Nauka, M., 2015)
4. A.A. Filippov, G.V. Pachurin, V.I. Naumov, N.A. Kuzmin, Metallurgist **59**, 810-815 (2016)
5. Y. Furuya, S. Matsuoka, J. Iron and Steel Inst. Jap **89(10)**, 1082–1089 (2003)
6. P. Lukas, L. Kunz, L. Navratilova, et al., Materials Science and Engineering **528**, 7036–7040 (2011)
7. Y. Furuya, Mater. Lett **112**, 139–141 (2013)
8. K.A. Molokov, V.V. Novikov, N.P. Vasilchenko, Bulletin of the Engineering School of FEFU **3(36)** (2018)
9. E.A. Moiseychik, Vestnik MSCU **11**, 58-67 (2014)
10. V.V. Galkin, Forging and stamping production. Processing of materials by pressure **8**, 11-14 (2014)
11. G.V. Pachurin, *Resistance to corrosion fatigue of technologically processed metals and alloys* (Vologda: Infra-Engineering, Moscow, 2022)
12. A.N. Gushchin, G.V. Pachurin, Ferrous Metallurgy **2**, 46-51 (2007)
13. I.O. Leushin, A.Yu. Subbotin, I.V. Geiko, Ferrous metals **10**, 48-53 (2017)
14. G.V. Pachurin, V.A. Vlasov, Metal Science and Heat Treatment **56(3–4)**, 219–223 (2014)
15. T.A. Bogdanova, Bulletin of the Siberian State Aerospace University named after academician M.F. Reshetnev **2**, 239-241 (2018)
16. Y. Estrin, A. Vinogradov, Acta Materialia **61**, 782–817 (2013)
17. V.V. Sizov, V.E. Gromov, Y.F. Ivanov, Steel in Translation **42(6)**, 486-488 (2012)
18. Y.F. Ivanov, K.V. Alsaraeva, V.E. Gromov, N.A. Popova, S.V. Konovalov, Journal of Surface Investigation **9(5)**, 1056-1059 (2015)
19. G.V. Pachurin, V.V. Galkin, V.G. Pachurin, *Fatigue resistance of structural materials at different temperatures* (TNT, Stary Oskol, 2023)
20. A.N. Gushchin, G.V. Pachurin, Bulletin of Mechanical Engineering 7, 34-38 (2009)
21. G. Pachurin, D. Goncharova, A. Filippov, et al., Eastern-European Journal of Enterprise Technologies **5(12-95)**, 31–37 (2018)