The effect of the grain size on the cycle life of spring steel 50 CrMnV

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Abstract. Most of the breakdown of machine parts and metal products during operation is fatigue-related due to the impact of load cycling during operation, which often leads to serious financial losses, and sometimes even fatalities. Therefore, the issues of increasing cycle life are relevant. In this work, we propose a method for predicting the cycle life of spring-type steel: the expected cycle life of steels 50CrMnV and 60SiCr in the range of 10⁵-10⁶ cycles can be preliminarily estimated using the equation depending on the grain size. The method allows predicting the cycle life and significantly reducing the time of its evaluation for steels such as 50CrMnV and 60SiCr by eliminating long-term fatigue tests. In addition, it also allows choosing the best performance from process treatments for the cycle life parameter without long labor-intensive fatigue tests.

1. Introduction

One of the most important tasks of the industry is to accelerate the development of a process database to ensure competitive products in the domestic and international markets [1-4]. The quality of machine-building products is characterized by their performance properties [5-9].

During operation, most machines and equipment are exposed to load cycling, thus, the most common type of fractures is fatigue failure, which often leads to serious financial losses and sometimes fatalities [10-12]. Therefore, the issues of fatigue life of parts, components, machines and devices in general are priority areas of modern science and the most important task of industry.

In industry, metal products are widely used, which are made by various processing methods. As a rule, all strength metal parts of machines are made from blanks obtained by hot or cold forming [13-15]. Various operating conditions differ in size, nature of the load, temperature conditions, and environment, which have different effects on the processes of metal hardening [16, 17] and its resistance to fatigue failure. Many parts of machines and structures made from such blanks must withstand a huge number of loads and stresses.

Depending on a number of factors, changes in loads can occur either within the deformation or stress limits. Constant interest in the problem of fatigue failure of metals and alloys is associated with the problems of fatigue failure of critical parts of metal structures, since the brittle destruction of such parts is often preceded by the growth of a fatigue crack, which reduces the load-bearing capacity. The use of fracture mechanics approaches made it possible to evaluate and predict the crack resistance and cycle...
life of metal structures. It is necessary that the methods of testing metal materials for fatigue and fatigue crack growth are sensitive to the structural condition of the material. In addition, during fatigue tests, the kinetics of damage accumulation can be traced.

To date, in the process of designing metal products, there is no single technical plan of pressure treatment, taking into account the prediction of cycle life and the relation between the deformable state of the metal and the structure formed by it. While there is a lack of effective means of information support of engineering and design, which concerns forming processes and cycle life of the material obtained as a result of conversion technologies.

The number of products in the form of forged products and sheet blanks are formed of different microstructures, which is characterized by grain size, structure and residual stresses of different levels. The main thing in fatigue failure is not the average characteristics of strain resistance, but the measurements in specific places and elements of products that are primarily responsible for their service life. For the relation of local deformed measurement with their structural changes, their quantitative assessment is necessary.

It is important to offer information support for the process engineering of manufacturing plastically deformed metal products with specified fatigue characteristics. The current practice of process engineering does not allow us to develop technologies for metal forming, based on the requirements for their service properties, in particular, cycle life.

The factors that affect the structural condition of the material including grain size, type of microstructure and heat treatment, and residual stresses at the micro and substructure levels. At the same time, many domestic and foreign researchers note that the most important structural parameter of polycrystalline metal materials that affects the origin and propagation of cracks is the grain size, since grain junction lines can be effective barriers to sliding processes.

In high-strength metal materials, the determining structure factor may be the size of the sub-grain or one of the structure components. Most often, as the grain size decreases, the fatigue strength of samples increases, although grinding the structure does not always lead to a change in service life.

Plastic deformation in the cold or hot state affects the structure of the metal at all its levels, and it can simultaneously be combined with heat forming. At the level of fine structure, it changes the density and structure of defects in the crystal lattice, at the micro level - the grain size, morphology, and the value of residual stresses, at the macro level it causes residual macro stresses due to uneven deformation in the measurement and texture of the workpiece. The main technological factors include: the degree of deformation, its mechanical schematic, and temperature-speed processing conditions. For the entire product as a whole, the service properties are also affected by the inhomogeneity of the structure in the entire part. It is determined by the size of the part, as well as the geometry of structure elements or individual measurement of the part (blank), which are the most loaded and responsible for the service life of the product. The latter factor, in particular, has a great influence, since under real operating conditions, as a rule, the main load is taken by specific elements: in fasteners (nuts, bolts) - thread; in elastic elements (springs) - internal flat surface; in sheet stiffness - rifts; in cutting products (axe-knife group) - blade, etc.

A fairly large number of both foreign and domestic studies are devoted to the fatigue of structured materials, a review of which is presented in the works. They provide information on the fatigue resistance of metals and alloys deformed at room temperature and uniform loading.

During conversion technology processes of the source material by pressure processes, the mechanical properties of metals and alloys depend on the structure determined by the conditions of their processing. There is a clear relation between the structure parameters, in particular the grain size, and the mechanical and service properties of the metal.

The grain size represents the structure parameter that is most easily distinguished and that can establish analytical relation between structure and properties. This allows to indirectly evaluate the mechanical characteristics and service properties of the material, and as a result, the technical specifications of major products set the grain score.
Hot forming of metals and alloys has a huge application in production in all its forms. Under conditions of hot deformation at temperatures above 0.4 melting temperature, the process of recrystallization occurs, which is reduced to the formation of new grains to replace the deformed ones.

As the main parameter affecting the fatigue resistance of plastically deformed metals and alloys under hot processing conditions, it is proposed to consider the size of the recrystallization grain, since the cycle life of the material decreases with an increase in the degree of recrystallizing.

2. Materials and methods
This paper presents the results of studying the relation between the structure formed by the manufacturing technology and the fatigue resistance of metal products.

Micrographic investigation was carried out with 50CrMnV spring steel in order to determine the grain size for samples with different degrees of process induced distortion (degree of reduction). For this purpose, flat samples were cut by electrical discharge machining from rolled into wedges and heat-treated metals.

The grain size was determined by the length of the rolled sheet. For this purpose, based on the use of optic digital microscopy, a specialized software package was developed using the NI Vision software and the LabVIEW development environment of National Instruments.

The plan includes two programs. The first one provides quantitative measurements and calculation of the metal microstructure. To do this, digital photos of the microstructure are binarized, as a result of which the image elements are divided into objects – grains and background.

The samples were tested for fatigue (symmetric bending) at the same stress, providing $10^5$-$10^6$ cycles.

3. Results and discussions
The microstructure along the entire length of spring steel sheet 50CrMnV consists of sorbite and ferrite (Figure 1).

![Figure 1. Microstructure of the studied zones of the spring leaf: a-central hole; b-cross-section with the reduction degree of 40%](image)

The analysis of the experimental data as a result of fatigue tests with different degree of reduction has shown that when removing layers of rolled into wedges metal, sheet fatigue life of the samples increases with the reduction degree of 23%, but the fatigue life of the samples reduces with the reduction degree of 40%.

Figure 2 shows a comparison of the results of the fatigue test with the grain sizes of the samples.
Figure 2. Dependence of the number of cycles to the failure of steel 50CrMnV on the grain size

According to the mathematical processing of experimental data, the equation of the dependence of the number of cycles to failure (cycle life) on the grain size of steel 50CrMnV is obtained:

\[ Y = -237125.08 \ln(x) + 1336448.22 \quad R^2 = 0.93, \]  

where \( Y \) is the number of cycles to failure; \( x \) is the grain size, microns; \( R \) is the correlation coefficient.

To implement the method, it is sufficient to determine the grain size of steel and calculate the expected cycle life using equation 1.

The method allows one to predict the cycle life and significantly reduce the evaluation time for steel 50CrMnV, for which it is enough to determine the grain size and calculate the expected cycle life using equation 1. In addition, this method allows choosing the optimal mode from competing processing treatments for the cycle life parameter by comparing the grain size: the grain is smaller, the cycle life is higher.

Experimental verification of the method was also carried out on steel 50CrMnV and 60SiCr. The results confirmed the reliability of this method. Deviations of cycle life in experiments from the data obtained by equation 1 did not exceed 6%. This gives reason to believe that the grain size is the main control parameter that characterizes fatigue resistance.

4. Conclusion

The proposed method allows predicting the cycle life and significantly reducing the time of its evaluation for spring steel 50CrMnV, by eliminating long, expensive, energy - and time-consuming fatigue tests.
In addition, it also allows choosing the optimal performance from competing processing treatments for the cycle life parameter without conducting long-term labor-intensive fatigue tests by simply comparing the grain size of steels: when the grain size is smaller, the cycle life is higher.

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