Properties of metallic materials near the edges of fatigue crack

A V Kornilova¹, Kyaw Zaya²*, Thet Paing³, M F Dobrolyubova⁴

¹Peoples' Friendship University of Russia (RUDN University), Miklouho-Maclay, 6, Moscow, 117198, Russia
² Moscow State Technological University "Stankin", Vavkovskiy lane, 1, Moscow, 127055, Russia
³ Military Computers and Technological Institute, Hopong, 06091, Myanmar
⁴ Crimean Engineering and Pedagogical University named after Fevzi Yakubov, Uchebny lane 8, Simferopol, 295015, Republic of Crimea, Russia

*Email: k.kyawzaya@yandex.ru

Abstract. This paper discusses the condition in the magnetic and mechanical properties of metal materials near the edges of a fatigue crack (sample example – steel20). On the special samples with straight fatigue cracks, the coercive force and hardness were measured near the crack edges. The coercive force drop on the crack was 25%. Therefore, if the magnetic properties of ferromagnetic material fall during the survey, this means that there is a crack in the structure being examined, which is not always detected visually or by non-destructive testing methods with a different physical basis. The obtained results of hardness measurements allowed us to formalize the dependence of the straight crack depth on the drop in hardness near its edges relative to the same parameter in the defect-free section. By calculating and experimentally, the relationship angle between normal and the tangent to the surface of crack inclination was identified and formalized. The results of the work can be used in the technical diagnostics of engineering objects.

Keywords: fatigue crack, flaw detection, hardness, indenter, coercive force, crack edges.

1. Introduction

The main cause of machine parts failure for various purposes is a nucleation and growth of fatigue cracks. In figure 1, a – shows the dynamics of global publication activity on this topic since 2011, b – distribution of patents by country over the past 10 years.

![Figure 1. Distribution of publication activity (a), patents by country(b).](image-url)

Obviously, over the past 10 years, interest in the topic of fatigue cracks has increased, and the bulk of patents are in industrialized countries. Review of the literature on this subject has shown that the
main problem is to prevent the development of already formed defects. Studies of the crack growth process are devoted to [1-3]. The first step to stop crack growth is study to the changing the properties of materials near the crack edges and determine its parameters [4-6]. There are currently several methods of determining the depths and crack inclination angles, but each has its limitations. Among the various non-destructive methods to measure the depth of a crack, the most widely used are eddy current testing [7-9] and infrared thermography [10-15]. Along the edges of fatigue cracks, the magnetic and mechanical characteristics of the material change due to the accumulation of damage and a hardening/softening factor. However, we have not been able to find dependencies in the literature, that allow us to establish a relationship between mechanical or magnetic characteristics and parameters of fatigue cracks. With the purpose of establishing and formalizing these relationships were studied, the results are shown below. These dependencies will simplify the reliable performance of technical diagnostics.

2. Materials and methods
The research carried out is experimental and computational analysis. For the computational experiment, we used finite element analysis (FEA) of the SolidWorks. To conduct a full-scale experiment, the following devices were used:

- Coercimeter KIM-2M
- Electric potential crack meter-281M
- TK-2M hardness gage

For research, samples were made in accordance with GOST 1497-84 [16] (proportional flat sample with heads, type – I) figure 2, a (a₀=6mm).

![Figure 2. The samples used in the experiment.](image)

Material of samples are steel20 GOST 1050-2013 (USA – 1020, European Union – C22, C22 E). Before the research, specially made samples were cyclically loaded on the universal testing machine.
"Schenck–Hydropuls–100" manufactured by CARL SCHENCK AG, until the first visually detectable cracks appeared.

3. Results and discussion
After radiography, 8 samples with “straight” cracks were taken for further investigation (figure 2, b), i.e. cracks which normal to the crack edges is parallel to the tangent to the surface at the point where the crack exits it. The following measurement parameters were applied: demagnetization current – 155mA, pulse magnetization – 3. In each sample, the coercive force (magnetic characteristic of ferromagnet) was measured using a portable coercimeter KIM-2M. In each sample, the coercive force was measured over the defect (Hc_{mp}) and in two defect-free areas (Hc_1 and Hc_2) (figure 3, a). Then, the average value of the coercive force (Hc) by two measurements (Hc_1 and Hc_2) and the ratio (Hc/Hc_{mp}) were determined.

![Figure 3. Measurements area in the sample.](image)

In addition, the hardness was measured in each sample. The hardness measurement results are smaller spread than the structure-sensitive coercive force method. The Rockwell method was chosen for the experiments (scale – C with load 150kgf (1472 N) and indenter 120° diamond spherocional). The hardness was measured at the edges of the fatigue crack and at defect-free areas of the samples (figure 3, b). The crack depth was determined by electric potential crack meter-281M.

| Samples | Hc, A/m | Crack depth, mm | Hc/Hc_{mp} |
|---------|---------|-----------------|------------|
|         | Hc_1 | Hc_{mp} | Hc_2 |                  |
| 1       | 253  | 192    | 217  | 4.0              | 1.22       |
| 2       | 186  | 180    | 217  | 4.2              | 1.11       |
| 3       | 197  | 136    | 205  | 3.3              | 1.44       |
| 4       | 118  | 112    | 149  | 3.5              | 1.19       |
| 5       | 180  | 143    | 217  | 5.5              | 1.38       |
| 6       | 289  | 253    | 301  | 3.0              | 1.16       |
| 7       | 253  | 205    | 241  | 1.7              | 1.20       |
| 8       | 217  | 174    | 241  | 1.0              | 1.31       |
|         |       |        |      | Hc/Hc_{mp}       | 1.25       |

In table 2, it is assumed that HRC_0 – the surface hardness of the test samples (the average value of defect-free areas) is 27, HRC – hardness measurement near the crack edges and Δ – as a percentage of reducing the hardness at the crack edges from the defect-free areas show that the dependence of the crack depth on the reducing of hardness at the crack edges from the defect-free areas as a percentage (figure 4).
Table 2. Hardness (HRC) near the crack edges in samples

| Hardness HRC | Crack depth l, mm | Δ=100-(HRC·100/HRC₀) |
|--------------|------------------|------------------------|
| 6.0          | 5.7              | 77.78                  |
| 6.5          | 4.9              | 75.93                  |
| 7.0          | 4.1              | 74.07                  |
| 9.5          | 4.3              | 64.81                  |
| 9.5          | 4.8              | 64.81                  |
| 10.5         | 5.6              | 61.11                  |
| 12.0         | 3.0              | 55.56                  |
| 12.0         | 3.1              | 55.56                  |
| 13.3         | 4.0              | 50.74                  |
| 13.5         | 4.1              | 50.00                  |
| 14.5         | 2.6              | 46.3                   |
| 15.0         | 4.6              | 44.44                  |
| 15.7         | 3.5              | 41.85                  |
| 16.0         | 3.3              | 40.74                  |
| 17.0         | 2.7              | 37.04                  |
| 19.0         | 4.2              | 29.63                  |
| 26.3         | 1.5              | 2.59                   |

HRC=13.1  l=3.9  Δ=51.4

Figure 4. Graphical dependency of $l=f(\Delta)$. The dependency of $l=f(\Delta)$ is approximated by the expression:

$$l = 0.043 \cdot \Delta + 1.672$$

For example, if the hardness drops from 27 HRC in the defect-free zone to 13.3HRC near the crack edges, according to the equation (1), crack depth is 3.85mm (according to measurements 4.0mm). Inaccuracy is 3.65%.

According to the average coefficient of elasticity of linear function dependence [16]:

$$E = 0.043 \cdot \frac{\Delta}{l} = +0.57$$

This means that, if $\Delta$ increase is 1%, the crack depth (l) will change by 0.57%. The “+” sign indicates that as parameter (Δ) increases and the crack depth (l) also increases.
The computational experiment was performed to determine the functional dependence at the "non-
straight" crack inclination angles by measuring the displacement of its edges. Models were constructed
(figure 5) with a different crack inclination angles with constant value of defect disclosure (the
minimum distance between two nodes – 0.1 mm). In the experiment, apart from the crack inclination
angle (α°) was also made its depth (l, mm). The force is corresponded to the force of measuring
hardness on a Rockwell scale C – 150 kgf. The displacements along the crack edges were measured
under the application of an alternating load to its edges X1 – blunt edge and X2 – sharp edge (the
longitudinal section of the sample with crack). In figure 4, α – angles α1 and α2 are not equal, this is
due to the received value of the crack disclosure.

Figure 5. Model for determining the dependence of crack
inclination angle for changing the displacement at its edges
(a) and a finite element grid (b).

The results of a two-factor computational experiment are shown in table 3. And the graphic
interpretation of the ratios X1/X2, crack inclination angles and crack depths are shown in figure 6.

Table 3. Calculations results

| α° | X1/X2 | l=2 mm | l=3 mm | l=5 mm |
|----|-------|--------|--------|--------|
| 10 | 1.97  | 2.02   | 2.05   |
| 20 | 3.72  | 3.84   | 4.09   |
| 30 | 7.04  | 7.439  | 8.11   |
| 40 | 9.83  | 10.53  | 12.05  |
| 50 | 20.06 | 21.18  | 25.14  |
By using the least squares method, the following dependence was obtained with the coefficient of determination (approximation accuracy $R^2 = 0.9$):

$$\alpha^o = 16.1 \cdot \ln \left( \frac{X_1}{X_2} \right) + 1.5 \quad (2)$$

The assumptions made in the calculation and the above experimental studies allow the replacement in the ratio $X_1/X_2$ with $HRC_1/HRC_2$ in equation (2). Therefore, the equation (2) can be reformulated for practical application when performing operational technical diagnostics:

$$\alpha^o = 16.1 \cdot \ln \left( \frac{HRC_1}{HRC_2} \right) + 1.5 \quad (3)$$

Studies have shown that the parameters of fatigue cracks can be determined by measuring the properties of the material near its edges. In this experiment, two processes occur at the point of force application – the displacement of the crack edge at the point of force application (the dominant process, which depends on the crack depth and the angle between the normal and the tangent to the surface) and the indenter penetration into the sample (depends only on the mechanical properties of the material). In this case, the result of both processes is represents a certain complex value, unlike the measurement of hardness in a defect-free areas of the sample. When using the diamond cone with a constant force at the crack edges, complex indicator is the same for all samples with the crack. This means that, when measuring this parameter along the opposite sides of the crack, it is possible to determine the angle between the normal and the tangent to the surface of crack inclinations.

The crack cavity is filled with air and/or non-magnetic inclusions, whose magnetic permeability is less than the ferromagnet. Magnetic poles are formed along the crack walls, as a result the force lines coming to the surface, appear the defect scattering field. The analysis of the obtained results showed that the coercive force at "straight" cracks is decreases average 25% than, defect-free areas of the samples. This result can be extended to all structural low- and medium-carbon steels. If the magnetic properties of a ferromagnetic material fall during the survey, this means that there is a crack in the structure being examined, which is not always visually detectable, especially in large-sized parts, there have paint, grease, and industrial dirt on its surface. In our experiment, it was not possible to identify a clear correlation between the drop in coercive force over the crack and the crack depth, as well as between the drop in coercive force and the cross-sectional area, which stops resisting the load when the defect appears. This is due to the small sample of available test values with high sensitivity of the method.

4. Conclusions

Studies have shown that the properties of metals (mechanical and magnetic) near the fatigue crack edges differ in similar properties of defect-free metal. If the magnetic properties of a ferromagnetic material fall during the survey, this means that there is a crack in the structure being examined, which is not always detected visually or by non-destructive testing methods with a different physical basis.
It is experimentally determined that crack-like defects in structural steels have drop in the hardness (HRC), which in this case is a complex value, that takes into account the movement of crack edges at the point of force application and the indenter penetration into the sample. Based on experimental data, we obtained a functional relationship between the hardness (HRC) drop at the “straight” crack and the crack depth, as well as between the hardness ratios at the edges of the “non-straight” crack and the crack inclination angle. The obtained dependencies will allow us to quickly perform technical diagnostics of crank machine parts without the use of complex measuring systems.

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