On the nature of steel fatigue fracture

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Abstract: Experimental data confirmed that if steel cyclic stress reduces to less than tensile yield stress values, i.e., in case of high-cycle fatigue, the mechanism of fracture changes from dislocation to vacancy one. The authors based their findings on the fact that steel density determined by the method of liquid displacement is less than that of steel in both initial conditions and after fracture under the cyclic loads exceeding tensile yield stress values. In the latter case steel hardness increases, whereas the specimens fractured under the cyclic stresses less than their tensile yield stress values show no change in hardness. It means that in such a case metal fractures without strain hardening, i.e., undergoes brittle fracturing developing by vacancy mechanism rather than by dislocation one. As a result, such steel obtains the structure and properties similar to those appearing after its exposure to radiation, i.e., friability and brittleness.

Keywords: fatigue fracture, dislocation fracture, vacancy fracture, low-cycle fatigue, high-cycle fatigue.

1 Introduction

The hypothesis on changing the mechanism of fracture from dislocation to vacancy one under the cyclic stresses less than tensile yield strength found its experimental confirmation in steel density estimation. The authors demonstrated that steel density values can be used for residual life determining and forecasting. To estimate the rate of a fatigue crack growth we proposed in our previous work [1] to use $\bar{V}_{1cs}$ as the number of crack tip interatomic bonds broken within a single cycle of maximal variable stress $\sigma_{max}$. We found that when $\sigma_{max} > \sigma_{0.2}$ the value of $\bar{V}_{1cs}$ is greater than one and amounts to several hundred of broken bonds per cycle (low-cycle fatigue); at $\sigma_{max} = \sigma_{0.2}$ we have $\bar{V}_{1cs}$ is equal to one and $\sigma_{max} < \sigma_{0.2}$ results in $\bar{V}_{1cs} < 1$ (high-cycle fatigue). In the latter case, the bond is destroyed within several (multitude of) cycles instead of a single one given that one interatomic bond can only be broken as a whole and not part by part. In this context, the mechanism of fracture may change from dislocation to vacancy one. This work was performed with a view to either experimentally confirming or denying the above hypothesis. In case the density reduces in comparison with the initial value the hypothesis can be accepted, otherwise it is to be rejected.
2 Experimental results

To test the above assumptions a set of 3 mm thick flat "corset" specimens of 09Г2C (AISI A 516 55) and 20X13НЛ (AISI 420) steel grades underwent cyclic testing. Instron 8801 testing machine was used to conduct these tests at zero-to-tension stress cycle (stress ratio \( R = 0 \)) and cycling frequency of 20 Hz. Some of the specimens were tested under maximum cyclic stress \( \sigma_{\text{max}} \) less than tensile yield strength, others - at \( \sigma_{\text{max}} \) higher than tensile yield strength. The cyclic tests were preceded by tensile tests to determine the tensile yield strength \( \sigma_t = 360 \text{ MPa} \) for 09Г2C and the offset tensile yield strength \( \sigma_{\text{0,2}} = 255 \text{ MPa} \) for 20X13НЛ. After fracturing the specimens were used to cut out 35mm×30mm square blocks from their near-fracture zones to determine their density and hardness. To determine density the authors used liquid (distilled water) displacement method. The error of density assessment was ±1%. The hardness value registered was an average of five tests conducted on Instron Tukon 2500 machine under 1 kg load. The error in the hardness assessment was ±2.5%. The below Table contains the results of the experiments conducted.

Table. Cyclic fatigue tests results and fracture zone metal hardness

| Material   | Maximum cycle stress \( \sigma_{\text{max}} \), MPa | Up-to-fracture cycles number \( N \) | Density \( \rho \), g/cm\(^3\) | Hardness HV1, kgf/mm\(^2\) |
|------------|--------------------------------------------------|-----------------------------------|-------------------------------|-----------------------------|
| 09Г2C      | \( 330 (\sigma_{\text{max}} < \sigma_t) \)       | \( 911 \times 10^3 \)            | 6.90                          | 165                         |
|            | \( 420 (\sigma_{\text{max}} > \sigma_t) \)       | \( 60 \times 10^3 \)             | 7.40                          | 213                         |
| Metal in initial condition |                                      |                                   | 7.18                          | 170                         |
| 20X13НЛ    | \( 180 (\sigma_{\text{max}} < \sigma_{\text{0,2}}) \) | \( 98 \times 10^3 \)             | 5.70                          | 188                         |
|            | \( 300 (\sigma_{\text{max}} > \sigma_{\text{0,2}}) \) | \( 17 \times 10^3 \)             | 7.60                          | 210                         |
| Metal in initial condition |                                      |                                   | 7.27                          | 190                         |

The Table shows that after the cyclic tests the density of both steel grades has substantially changed in comparison with their initial condition. The density of 09Г2C reduced by 3.9% after testing under \( \sigma_{\text{max}} < \sigma_t \) and increased by 3% after \( \sigma_{\text{max}} > \sigma_t \) testing. The density of cast steel 20X13НЛ reduced by 21.6% after testing under \( \sigma_{\text{max}} < \sigma_{\text{0,2}} \) in comparison with the initial value, and increased by 4.5% after testing under \( \sigma_{\text{max}} > \sigma_{\text{0,2}} \). The data presented can be referred to as an experimental validation of the hypothesis concerned. It should be noted that cast steel 20X13НЛ shows higher spread of density values than that of wrought steel 09Г2C. This may be caused by increased amount of defects, e.g. pores and other imperfections of cast steel structure. At the same time, the values of density increase in cast and wrought steels observed after cyclic loading under maximum cycle stresses exceeding tensile yield strength are quite close to each other and as large as 3% and 4.5% respectively. When comparing the values of HV1 hardness taken before and after the cyclic tests one can see that the increase in 09Г2C hardness under \( \sigma_{\text{max}} > \sigma_t \), was as high as 25.3%, whereas the same value for 20X13НЛ under \( \sigma_{\text{max}} > \sigma_{\text{0,2}} \) amounted to 10.5%. This increase of both steels hardness and density can be accounted for by their work-hardenability, or strain-hardening. In comparison with their initial values the changes in both steels hardness observed after their cyclic tests under \( \sigma_{\text{max}} \) less than tensile yield strength appeared to be insufficient (by 1…3%) and within the limits of experimental error. This result can be deemed the second experimental evidence of the fact that strain-hardening known for its dislocation nature is absent and was replaced by vacancy mechanism of steel fracturing. It should be noted that the absence of strain-hardening signs to be observed during metallic materials fracturing speaks for its brittle nature. It should be reminded that metals and alloys are prone to increasing their vacancy amount when exposed to aggressive radioactive environments. This increase results is substantial density reduction, friability and embrittlement known as radiation friability and embrittlement. The results obtained make it possible to determine the cause for the appearance of Veller fatigue fracture diagram discontinuity [1]. During the vacancy fracturing a fatigue crack growth is dependent on the amount of vacancies at its tip required for this crack growth. In the period of vacancy accumulation the crack doesn't grow as

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the number of stress cycles increases, which results in a fatigue diagram horizontal plateau (step).

3 Conclusion

In order to substantiate the hypothesis proposed it was experimentally confirmed that the mechanism of fracture changes form dislocation to vacancy one under the cyclic stresses less than tensile yield strength, i.e. under high-cycle fatigue conditions.

It was found expedient to use metal density as a test parameter for metal parts and structures online inspection conducted to estimate their residual operation life.

References

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