Acoustic emission analysis of crack resistance and fracture behavior of 20GL steel having the gradient microstructure and strength

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Abstract. The crack resistances as well as fracture behavior of 20GL steel quenched with a fast-moving water stream and having gradient microstructure and strength are analyzed. Crack resistance tests with quenched and normalized flat rectangular specimens having different cut lengths loaded by three-point bending with acoustic emission measurements have been performed. The critical $J$-integral has been used as the crack resistance parameter of the material. Quenching with a fast moving water stream leads to gradient (along a specimen wall thickness) strengthening of steel due to highly refined gradient microstructure formation of the troostomartensite type. Quenching with a fast-moving water stream increases crack resistance $J_c$, of 20GL steel by a factor of ~ 1.5. The fracture accretes gradually with the load in the normalized specimens while the initiated crack is hindered in the variable ductility layer and further arrested in the more ductile core in the quenched specimens.

1. Introduction
Development of gradient microstructures is an efficient way of strengthening and increasing fracture resistance of critical components from carbon steels, e.g. parts of the rail transport (side frames of freight car trucks, etc.). Development of gradient microstructures in steels is possible using heat treatment which includes holding in the austenite temperature range followed by cooling with a fast-moving water stream (so-called spray quenching or jet impingement quenching). This technology is attractive in industry because it provides intensive heat transfer rate between the component and the quenchant and high heat removal capability. Such a heat treatment allows creating the gradient distribution of strength across a component cross section (high strength surface and ductile core). At that, compressive stress is developed on the surface which prevents crack initiation [1-6]. Taking into account the strengthening effect of spray quenching on steel mechanical properties [5, 6], its influence on the static crack resistance may not be obvious, the more so if the gradient nature of the microstructure and its cross-section toughness which are developed by this type of heat treatment are considered. In this regard, the main objective of this work was the study of crack resistance and fracture behavior of 20GL steel quenched with a fast-moving water stream, having the microstructure and strength gradient along the cross section using acoustic emission and fractography.
2. Materials for the study

The study was performed on the specimens cut from the side frames of the freight car trucks made from 20GL steel (Table 1). First, a 700 mm long part was cut out of the side frame as shown on the Figure 1a. The part was subjected to heating in the resistance furnace up to 950-970 °C and then to quenching with a fast-moving water stream during 2 minutes in a special quenching device which allows to cool the part from all sides using multiple pressurized water jets. Then, specimens with a central cut were cut out of the part, oriented in the longitudinal direction of the side frame (see Figure 1a). The same specimens cut out of the side frame in the initial condition were also studied for comparison (normalized at T=930-960 °C, 2 h, cooled in air). The wall thickness of the side frame which the specimens were cut out from (16-19 mm) did not allow making typical specimens for crack resistance tests, therefore special specimens were prepared and used. Their dimensions are shown on Figure 1b. The height of the specimens constituted \( b = 13.0\pm0.1 \) mm, specimens thickness, \( t = 10.0\pm0.1 \) mm, length, \( L_1 = 75.0\pm0.1 \) mm, cut depth, \( l = 1, 2, 3, \) or \( 4 \) mm (specimens with different cut length were tested), cut width, \( e = 2 \) mm, distance between the supports, \( L = 50.0\pm0.1 \) mm.

Table 1 – Chemical composition 20GL grade steel

|       | C    | Si   | Mn   | V    | Al   | S    | P    | Other                  |
|-------|------|------|------|------|------|------|------|------------------------|
| C     | 0.197| 0.336| 1.163| 0.10 | 0.035| 0.009| 0.013| 0.14 Cr; 0.092 Ni; 0.129 Cu |

Figure 1. Specimens used for crack resistance tests (a - scheme of cutting out the part and specimen from a side frame; b - specimen geometry and sizes)

3. Methods of study

3.1. Microstructure analysis and hardness measurement

The microstructure was studied on the cross-sections after etching with 4% alcohol solution of nitric acid using Axio Observer D1m Carl Zeiss optical microscope with \( \times 500 \) magnification. The microstructure of the specimens was studied in different points of the cross-section after quenching with a fast moving water stream (at different depths of the cooled surface).
Hardness was measured on the same specimens across the cross-section using Rockwell’s method and Buehler MacroMet 5101T hardness gauge with 1 mm step. C scale and 150 kg loading were used for the quenched specimens which have higher hardness, and A scale and 60 kg loading were used for the normalized specimens. The measured values were then converted to a single scale (HB) using hardness tables for the comparative analysis.

3.2 Mechanical tests and acoustic emission measurement

The tests were performed at room temperature following the three-point bending on the base of 50 mm using the universal Instron 150 LX test machine with active grab travel rate of 0.2 mm/min and maximum force of 150 kN. The tests were performed on flat rectangular specimens having different cut lengths (l=1, 2, 3, or 4 mm). The acoustic emission was continuously registered during the three-point bending tests simultaneously with the “load P – deflection f” curve registration. The acoustic emission (AE) method allows precisely determining the moment of crack initiation and controlling the material failure kinetics. In particular, this method was successfully used in works [7, 8] to study the static and cyclical strength of side frames of freight car trucks. Also, this method allows obtaining quantitative assessments of the crack sizes [9, 10]. In this work, the AE method was used both for determining the moment of crack initiation during specimen loading and for detailed study of mechanisms and kinetics of 20GL steel failure.

AE signals were detected with the CTS-19 piezoelectric transducer installed on the polished surface of a specimen through a layer of glycerol (Figure 2). AE signals after preliminary amplification (30±3 dB in 5 MHz frequency band) were recorded via the PXI-1042Q (National Instruments) modular computer platform controller with up to 10 MHz ADP analogous signal frequency sample in 70 dB dynamic range. The measured parameter was peak amplitude of AE signals. The “load P – deflection f” curves were time-aligned with the acoustic emission diagrams after tests.

![Figure 2](image)

Crack initiation in the cut tip was determined using acoustic emission (AE) signals which exceeded the noise level significantly, with simultaneous recording of the critical load \( P_c \) corresponding to this crack initiation. Analysis of the crack propagation mechanism and kinetics was performed using the analysis of AE signals quantity, occurring after the crack initiation and their peak amplitudes (\( U_{AE} \), \( V \)). Crack initiation on the surface of the specimens was also observed visually using a binocular during loading and after it was stopped following registration of high-power AE pulses.

3.3 Critical J-integral value calculation

The linear fracture mechanics parameters are usually used to assess the crack resistance of brittle materials, e.g. stress intensity critical factor which does not depend on the specimen thickness (\( K_{IC} \), MPa·m\(^{1/2} \)). Non-linear fracture mechanics parameters are used for ductile materials, for instance, the critical J-integral (\( J_{IC} \), kJ/m\(^2 \)) [11]. 20GL steel after normalization as well as after quenching with a fast moving water stream features medium strength and ductility so, a non-linear fracture mechanics parameter critical J-integral \( J_c \) was used as a parameter of the crack resistance.
Begley-Landes method was used to determine the $J$-integral [12, 13]. According to the method, the value of the $J$-integral for each selected deflection $f$ is determined taking into account the specimen thickness $t$ using the following formula:

$$J = \frac{1}{t} \frac{dA}{dl},$$

where $dA$ is the deformation energy by the crack initiation moment, $dl$, crack (cut) length variation, $t$, flat rectangular specimen thickness.

Deformation energy $A$ was determined as the area under $P-f$ curve along the region from 0 to $f_c$. The value of $f_c$ was determined by the acoustic emission impulse. Calibration curves $A(f)$ were plotted for different cut lengths based on the determined values of the deformation energy. $J$-$f$ curves were plotted using the calibration curves $A(f)$ to determine the crack resistance parameter $J_c$. $J$-$f$ curves were further approximated by a linear function according to the following equation:

$$Y = kX + a,$$

where $Y$ is the energy divided by the crack growth value (J/m), $X$, cut length (0.001-0.004 m), $k$, specific (divided by the specimen thickness $t = 0.01$ m) mechanical energy per crack length unit. $J_c$ values were determined on the $J$-$f$ curves using previously determined $f_c$ values.

3.4 Fractography

The fracture surface after the mechanical tests was studied using the JSM-6610LV (JEOL) scanning electronic microscope with ×(100–2000) magnification. The pattern of fracture surface change along the full thickness of a specimen was determined from the cut to the opposite side of the specimen.

4 Results of the study

4.1. 20GL steel microstructure and hardness

The microstructure of the 20GL steel after normalization and quenching is shown on Figure 3 while the hardness distribution along the specimen cross-section is shown on Figure 4. Normalized specimens had a typical for such steels ferrite-pearlite microstructure along the cross-section with a grain size of 25±5 µm (Figure 3a). Hardness of the normalized specimens along the cross-section constituted ~53 HRA (~7-10 HRC), which corresponds to the value of ~200 HB on the Brinell’s scale.

![Figure 3. Microstructure of normalized (a) and quenched (b) 20GL steel.](image)

The microstructure of the quenched specimens represented a mix of the martensite-like fine microstructure and proeutectoid ferrite of different morphology located along the grain boundaries and inside of the prior austenite grains (Figure 3b). The volume fraction of the proeutectoid ferrite was growing to some extent while moving away from the quenched surface. The hardness of the
specimens after quenching changes from 38 HRC (~500 HB) at the cut tip to 32 HRC (~270 HB) at the opposite side of the specimen (see Figure 2). Decrease in hardness with the distance from the surface can likely be explained not only by the increasing volume fraction of the proeutectoid ferrite but by the change of the fine martensite-like microstructure type as well (the troostomartensite or troostite microstructure prevails near the quenched surface while the central part of the specimen is dominated by the sorbite microstructure).

![Figure 4](image)

**Figure 4.** Hardness distribution on the wall thickness of specimen from 20GL steel after quenching (■) and normalization (●)

Thus, the 20GL steel strengthening after quenching with a fast moving water stream is due to formation of the martensite-like fine microstructure. This microstructure changes to some extent with the distance from the quenched surface which promotes the strength gradient formation along the cross-section. The absence of martensite in the microstructure (martensite could form only in a limited portion as a part of the troostomartensite in the surface layer), along with the presence of the proeutectoid ferrite, ensures sufficient ductility of such a microstructure.

4.2. 20GL steel crack resistance

Typical P–f loading curves aligned with AE diagrams registered in crack resistance tests of the 20GL steel after normalization and quenching with a fast moving water stream are shown on Figure 5 (example of specimen with 1 mm cut depth). Significant difference was observed in the mechanical behavior of the normalized and quenched specimens in the following tests irrelevant of the cut length: loading curve deviation from the linear law (corresponding to the material yield strength) and loading drop (corresponding to the reached ultimate tensile strength) were observed in the quenched specimens at significantly higher load as compared to the normalized specimens. Crack initiation registered by large AE impulses was observed in the region corresponding to uniform plastic deformation in both states of 20 GL steel (quenched and normalized). Deflection values \( f_c \) were determined corresponding to the crack initiation moment during tests for each tested specimen. After that, the deformation energy \( A \) was determined for each specimen as the area under \( P-f \) curve along the region from 0 to \( f_c \). Based on the determined values of the deformation energy, \( A-f \) calibration curves were plotted for different cut lengths. They further were used for \( J-f \) calibration curves plotting (Figure 6). \( J-f \) curves were used to evaluate the crack resistance parameter \( J_c \), by the deflection \( f_c \), corresponding to the specimen deflection at the crack initiation moment.
**Figure 5.** $P$–$f$ loading curves aligned with AE diagrams under crack resistance tests of 20GL steel after normalization (a) and quenching (b).

**Figure 6.** Calibration curves $J$–$f$ for 20GL steel

It is clear from Figure 6 that the 20GL steel static crack resistance after quenching with a fast-moving water stream by $J_c$ parameter constituted 225±15 kJ/m² which is 1.5 times higher than in normalized state (150±15 kJ/m²). Such a behavior of the 20GL steel can likely be explained by the formation of the highly dispersed fine microstructure with a sufficiently high ductility margin. Besides, the energy to crack initiation could be influenced positively by the compressive stresses, which form in the surface layer after quenching.

**4.3. Mechanism of crack propagation**

Detailed comparative analysis of acoustic emission signals registered throughout the three-point bending test of 1-mm cut length specimens was performed to study the mechanisms of crack propagation in the 20GL steel after quenching and normalization. Acoustic emission diagrams aligned with the loading curves were shown on Figure 5. It is clear from Figure 5a that when loading the normalized steel specimens, the first AE signals (having low amplitude $U_{AE}$, less than 0.5 V) are registered at ~8 kN load and are likely to be related to the initiation of the material plastic deformation and, possibly, to a small microcrack initiation in the cut tip. One or several AE impulses of a sufficiently large amplitude ($U_{AE}$=0.7-1.0 V) corresponding to a macrocrack initiation in the cut tip are observed at load of ~10 kN. The initiated surface macrocrack continuously grew afterwards as the load increased. This process is accompanied by dozens of AE impulses with ~0.5 V amplitude.
Starting from the load of $0.9P_{\text{max}}$, the crack developed by macro-steps which was accompanied by several high-amplitude ($U_{\text{AE}} = 1.5–2$ V) AE impulses and load drop of $\Delta P \sim 0.3$ kN. The crack further propagated by steps at the load drop after $P_{\text{max}}$ has been reached. First microcracks on the quenched steel specimen surface are registered at higher loads than in normalized specimens ($P \sim 15$ kN). The crack initiation process is accompanied by AE impulses with $U_{\text{AE}} \sim 0.5$ V amplitude (Figure 5b). The forming surface cracks 15-45 µm long were observed in the specimen fracture surface after registering AE signals with amplitude over $U_{\text{AE}}=0.5$ V, rapid specimen unloading, thermal crack decoration (holding in a furnace at 150 °C, 40 min) and final specimen failure. Macrocrack initiation in the cut tip is registered by AE impulse of a sufficiently large amplitude ($U_{\text{AE}} = 1.5$ V) at the load of $P \sim 18$ kN. The cause of the crack arrest in quenched specimens is likely to be the development of a plastic deformation in its top which leads to the crack tip blunting and delay that was observed on the polished surface of the specimen. In case of further loading, the propagation of the main crack by large steps restarts at the maximum load and during load drop as well.

The fractography analysis showed that the 20GL steel in both normalized and quenched state, features fully ductile fracture with typical failure elements - dimples (Figure 7). In both states, non-metal inclusions are observed at the bottom of some dimples. However, the microstructure of the ductile fractures of the specimen after normalization and quenching was somehow different. Thus, a non-uniform dimple fracture is observed in the steel after normalization in which, along with a small deep dimples up to 10 µm in size, a sufficiently large number of large “flat” shallow dimples of $\sim 30$-50 µm size containing non-metallic inclusions (Figure 7a) can be observed. The degree of the plastic deformation development around such “flat” dimples is relatively high. The dimple fracture is more uniform in the samples after quenching, the large “flat” dimples formed on non-metal inclusions are rarer, and their size (diameter) is smaller (up to 20 µm). Most part of the fracture surface is covered with a “small-dimple” component with dimple dimension, as a rule, of less than 5-7 µm.

The disperse martensite-like microstructure formed during quenching with a fast-moving water stream ensures generally small-dimple pattern of the fracture surface. Large amount of ferrite in the normalized state represented by relatively large grains of about 25 µm in size, causes formation of large ductile fracture dimples and relevant decrease in the total length of the ductile ridges (which are walls of the dimples), all of this leading to decreased energy intensity of the fracture.

The results of the fractography analysis explain the significant difference in the crack resistance assessed by the energy parameter of the material fracture - the critical $J$-integral $J_c$. Thus, the higher energy intensity of the fracture process in the quenched specimens as compared to the normalized specimens is confirmed by the more highly dispersed dimple structure of the fracture surface in this state.
5. Conclusion
The study of the microstructure and hardness of the 20GL steel showed that quenching with a fast-moving water stream lead to the formation of the martensite-like fine microstructure and ensures formation of the strength gradient along the cross-section (surface hardness increased by a factor of 2.5, and by a factor of 1.5 in the core as compared to the normalized state). The crack resistance tests with acoustic emission measurement along with the fractography analysis showed that creation of the gradient strength and microstructure by quenching with a fast moving water stream increased the static crack resistance of 20GL steel by a factor of 1.5, as compared to the normalized state. During three-point bending loading of normalized specimens having uniform strength along the cross-section, the crack grows continuously by steps throughout the test duration while in case of quenched specimens having a strength gradient along the cross-section, the crack decelerates in the ductile core at a certain stage of its development.

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