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Experimental study of torsional impact fatigue of shafts

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Abstract

This paper presents a methodology to study the fatigue strength of shafts under repeated impacts. The equipment for repeated impacts was designed for torsion tests of shafts for the same loading conditions as in service. The stress concentration effect, due to a fillet radius between square and circular cross-sections of the axle, was emphasized. Five groups of shafts with radius between 0.5 and 3.2 mm from a number of 100 shafts with different notch radius were selected. Based on a model proposed by the authors for defining the energy reduction factor β due to a notch the variation of the notch sensitivity factor η versus fillet radius was analyzed for two different numbers of cycles. It was observed that for a high number of cycles ($N = 2 \times 10^6$ impacts) the behaviour is similar to that of traditional fatigue tests. Oppositely, at lower number of cycles the particular aspect of the notch sensitivity is highlighted in the limited durability domain.

1. Introduction

In order to avoid fatigue fractures of components and structures it is necessary to know the material's fatigue strength under conditions close to those in service. Generally, the fatigue tests are divided into two groups: tests with sinusoidal variation of the load and fatigue tests for other modes of variation in time of the loadings. First tests are intended to investigate the metallurgical aspects of the fatigue phenomenon, while the latter ones are intended to predict the operating life under conditions close to those of operation. The following tests belong to the fatigue tests with non-sinusoidal variation: the non-impact fatigue tests like multiaxial fatigue tests, fatigue tests with spectrum loading, random load fatigue tests, and the impact fatigue tests.

Impact fatigue tests are based on repeated impacts between a hammer and a specimen. In this case the problem is much more complex as each impact leads to a dynamic contact and to the appearance of stress waves, which propagates in the bodies being in contact. This is the reason, for which impact fatigue tests are classified as the so-called *direct impact* fatigue tests and *indirect impact* fatigue tests [1]. The former tests have the purpose to study the local deformations and the degradation of surfaces in contact [2], while the latter ones are meant to study degradation in a volume as a consequence of propagation of impact waves from the contact area in a strengthening component considered [3].

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The most researches till now have a purpose to estimate some material's characteristics for tensile or bending indirect repeated impacts [4]. The reasons for these tests is to point out in what way they bring new features as compared to non-impact fatigue tests. It is obvious that some comparisons between impact fatigue tests and non-impact fatigue tests are more difficult to be made due to the type of the specimens used, the supports stiffness as well as durability assessment parameters [5]. Very few researches were performed till now on the durability assessment of some materials at repeated torsional impacts. This paper presents some results obtained in the Fatigue and Impact Laboratory of the "Politehnica" University of Timisoara, both for specimens and real structure like low-diameter shafts.

2. Features of material fatigue at repeated torsional impacts

The torsional impact fatigue strength is very important for power transmission systems. The research into the material's behaviour at repeated torsional impacts has not been extended to the current practice of the material testing laboratories. This is due to experimental difficulties to obtain, and requires special devices.

Some of the initial researches into fatigue torsional impact have been performed by Maekawa and Hida [6] in order to point out the influence of a dimensional factor on the fatigue strength under these stress conditions. The experimental tests on a carbon steel JIS SS41, with ultimate tensile strength $\sigma_u = 666.4\,\text{MPa}$ and elongation $\varepsilon_f = 21\%$, have been performed on a special equipment, where the hammer consisted of a straight bar, which is lifted by means of an eccentric device. The hammer falling height is the parameter which modifies the intensity of the repeated impacts. The falling height has also been used by the authors as a basic parameter to estimate and compare the number of cycles up to the fracture for the circular specimens of various shapes and length [6]. Figs. 1 and 2 present the obtained experimental results, which justify the importance of the specimens length, shape and fastening mode for the life in terms of the number of impacts. The research for steel JIS SS41 have been supplemented by the analysis of the elastic waves propagation using circular specimens of the same shape made of PMMA.

In order to estimate the behaviour of the steel 45KHN2 MFA, with yield stress $\sigma_y = 1380\,\text{MPa}$, ultimate tensile strength $\sigma_u = 1650\,\text{MPa}$ and elongation $\varepsilon_f = 5\%$ used e.g. for damping bars, the authors have adapted a special device for applying the repeated impacts, which provides a pure torsion stress in specimens. The stress spectrum has been recorded by means of a transducer fixed on the control lever of the device [7]. Besides the torsional impact tests, non-impact fatigue tests were also performed on a torsional test rig with pulsating

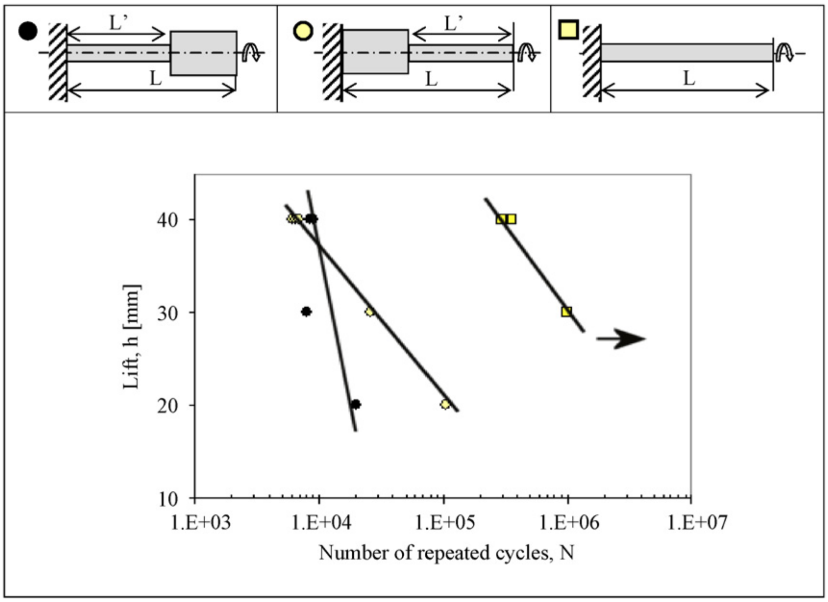

Fig. 1. Experimental results for torsional impact fatigue (after Maekawa and Hida [6]).

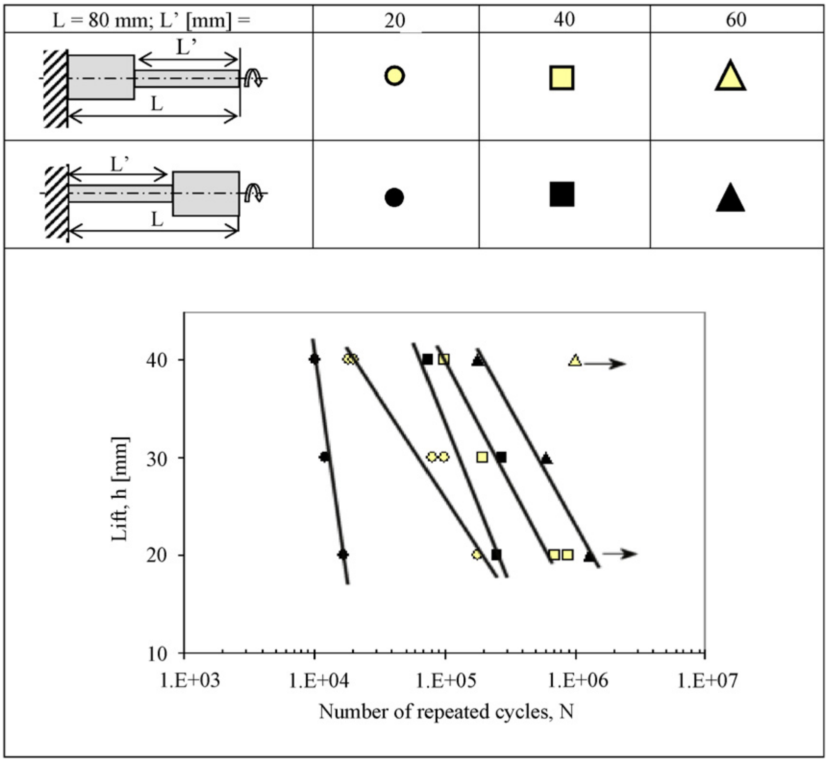

Fig. 2. Experimental results for torsional impact fatigue (after Maekawa and Hida [6]).

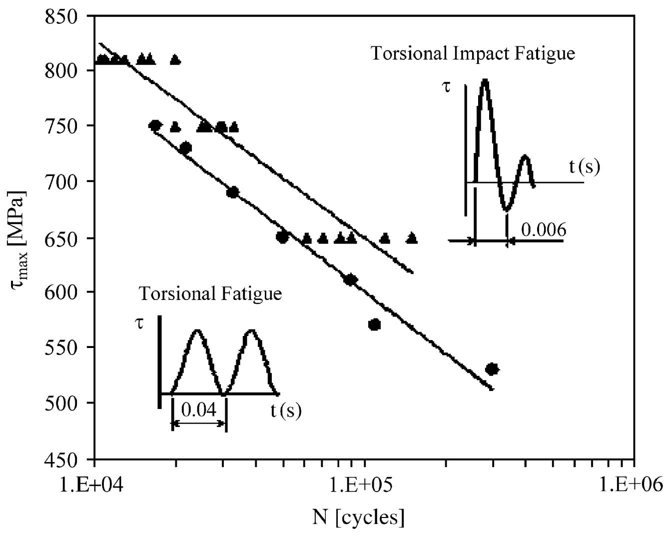

Fig. 3. Fatigue life curves for 45HN2 steel at fatigue torsion (●) and impact fatigue torsion (▲) (after Dumitru [7]).

cycles. Durability curves for the two modes of applied load are presented in Fig. 3. It is emphasized that durability at repeated impacts in the analyzed domain is higher than that obtained for the non-impact pulsating torsion. The experimental results are in accordance with those obtained in the cases of impact and non-impact tensile fatigue by other authors [8,9].

3. Impact fatigue durability of a shaft

3.1. General considerations

The proper operation of a mechanism can be impeded by fracture of a shaft, which is an important component of the structure. A shaft with a worm gear attached and supported by two bearings is studied. During the operation, the shaft is blocked by the worm gear and the impacts are transmitted to the shaft by means of a lever attached to the other end (Fig. 4). Under the impact action the shaft is loaded in torsion and bending. Small dimensions of the shaft as well as the type of its supports make the bending effect insignificant.

The lever, by means of which impacts are transmitted to the shaft, is attached to it by a square head. The transition from a square section to a circular one is a fillet with radius *r* (Fig. 5) that causes stress concentration. This concentrator has been proved to be extremely dangerous under the repeated impact loading, determining initiation of fractures. Currently, there is no mechanical model and mathematical theory describing the complex phenomenon of the stress concentration at torsional impact fatigue.

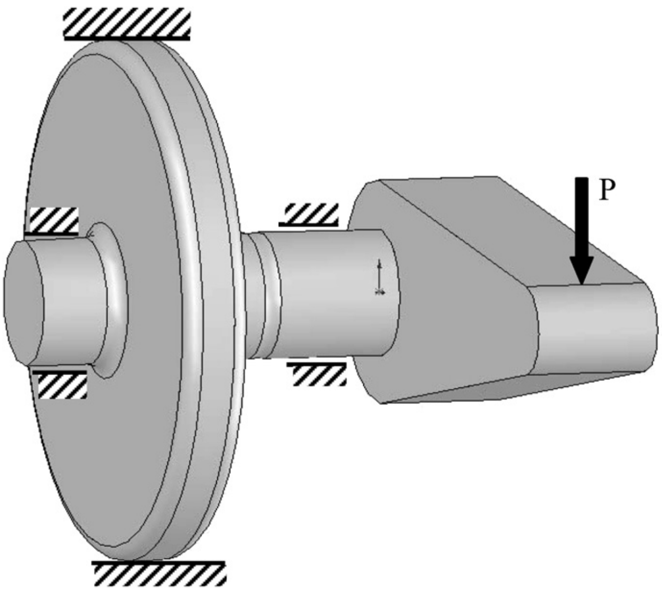

Fig. 4. Shaft with the loading lever.

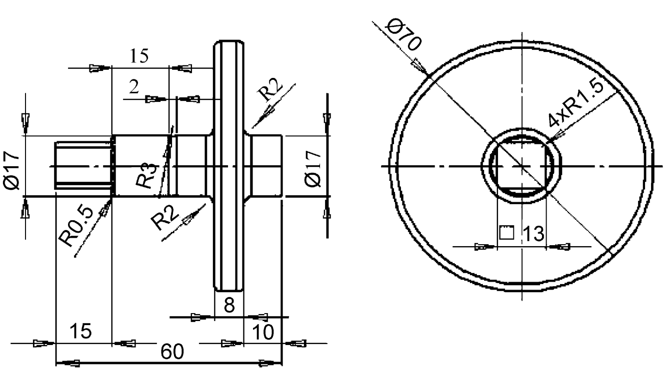

Fig. 5. Specimen for torsional impact fatigue tests.

Table 1
Chemical composition of 40Cr10 steel

C	Si	Mn	Cr
0.42	0.29	0.59	0.85

Table 2
Static tensile mechanical characteristics

	Young's modulus, E (MPa)	Ultimate tensile strength, σ_u (MPa)	Yield strength, σ_y (MPa)	Proportional limit, $\sigma_{p0.01}$ (MPa)	Elastic limit, σ_{e10} (MPa)	Percent elongation, δ_{10} (%)	Reduction of area, Z (%)
Mean value	2.05×10^5	697.3	498.4	481.11	446.5	16.47	66.93
Standard deviation	0.0345×10^4	1.38	2.34	2.15	1.97	1.46	1.18

Table 3
Static torsion mechanical characteristics

	Shear modulus, G (MPa)	Yield stress, $\tau_{0.3}$ (MPa)	Proportional limit, $\tau_{0.015}$ (MPa)	Elastic limit, τ_{10} (MPa)
Mean value	8.34×10^4	342.6	308.9	281.2
Standard deviation	0.248×10^3	1.26	1.23	1.87

The shaft's material is a low-alloy steel 40Cr10, with chemical composition presented in Table 1, which was exposed to a normalizing treatment. The service of shafts reveals failures around stress concentration and a further stress relief treatment was applied. Static mechanical parameters, conventional for traction and torsion were determined from testing of 20 proportionate specimens ($\varnothing$ 10 mm). The results are presented in Tables 2 and 3.

The durability tests at repeated impacts were performed on real-size specimens with the following fillet radius: $r = 0.5$, 1, 1.5, 2.5 and 3.2 mm. Some elements of the kinematics' chain have been strengthened in such a way so that to produce fracture in the shaft.

Initially, a static test has been performed in order to determine the fracture energy and the maximum breaking force of the shaft. The test has been performed in steps and the mean values for ten specimens were obtained $E_{st} = 295$ J and $F_{max} = 9.2$ kN on the basis of the F–δ_v diagrams, where δ_v represents the lever displacement on vertical direction of loading point.

A single impact tests using a weight with hammer of Pellini type allowed the determination of the shaft dynamic fracture energy E_d, which was between 396 and 402 J. In all the cases, the shaft has a fracture in the area with stress concentrator in a plane normal to the longitudinal axis.

3.2. Equipment for fatigue impact torsion tests and calibration

The test rig uses a guided hammer moved by a cam mechanism, Fig. 6. The impact energy can be modified by adding supplementary weights on the top of the hammer or by changing the height of the hammer. The shaft was fixed in a special device in order to reproduce the in-service conditions, Fig. 7. The stiffness of the system was checked to be close to the in-service conditions, using two strain gauges, one fixed at 45° on the shaft and one on the loading lever [10].

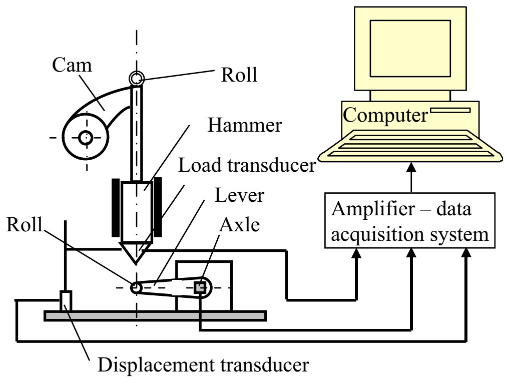

Fig. 6. Schematic of the equipment for torsional impact fatigue.

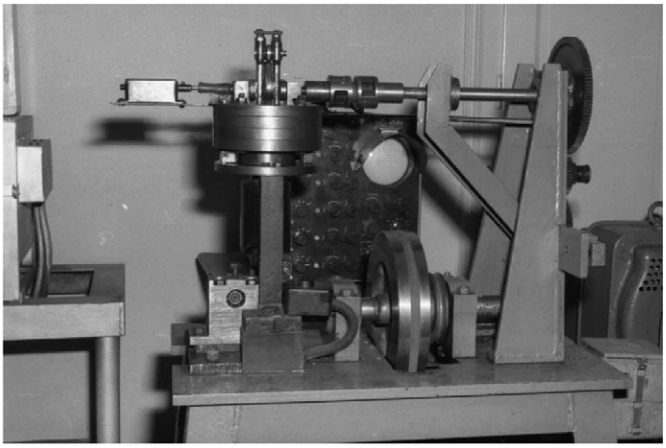

Fig. 7. Experimental equipment for torsional impact fatigue.

The gaps and the height were controlled and checked periodically during the impact fatigue tests in order to keep constant the impact energy. The purpose of the equipment calibration was to determine the real energy of a single impact E_0, since with all measures to reduce the friction, the movement of the hammer cannot be considered as a free fall. An indirect way was used based on the height of the hammer and time, to determine the hammer's acceleration g, the hammer's speed in the moment of impact v_0 and the real energy E_0:

$$v_0 = \sqrt{2gh'}, \quad E_0 = \frac{mv_0^2}{2}. \tag{1}$$

In the second stage of the calibration, some correlations between various parameters were established: like deformations and forces, forces and energies, since on different test equipments or by direct measurements in-service various results were obtained in different units. The results of the measurements allow the following conclusions:

- the equipment respects the single impact condition. This means that each loading cycle has one impact without other uncontrolled impacts, which could appear after first impact.
- a linear correlation can be assumed between deformations and forces, and between forces and energies. The averaged values of errors were below 2%. This circumstance is essential for generalizing the results obtained on this equipment.

3.3. Fatigue life

The durability curves in (E_0, $\log N$) coordinates were obtained for five different fillets, with the radius $r = 0.5$, 1, 1.5, 2.5 and 3.2 mm. Verification of the radius of fillet for a transition region from cylinder to square was performed with an optical microscope with $50\times$ magnification.

Each fatigue life curve was plotted on the basis of the tests at four energy levels for a limited durability of 2×10^6 repeated impacts, Fig. 8. Each point from Fig. 8 represents the average life of five specimens. These curves demonstrate importance of the stress concentration effect when the loads are applied by impacts.

In order to emphasize the particularities of impact fatigue the notch sensitivity factor η versus the radius of notch root r was plotted in Fig. 9, where η was defined according with [11]:

$$\eta = \frac{\beta - 1}{K_t - 1}, \tag{2}$$

where K_t is the stress concentration factor, and β represents the energy reduction factor by notch.

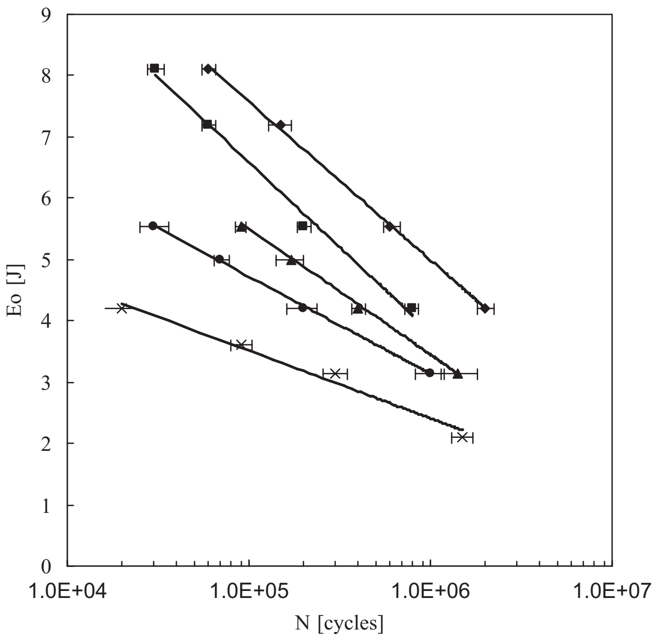

Fig. 8. Fatigue life for torsional impact fatigue for different notch radius. (∗, $r = 0.5$ mm, ●, $r = 1$ mm, ▲, $r = 1.5$ mm, ■, $r = 2.5$ mm, ◆, $r = 3.2$ mm).

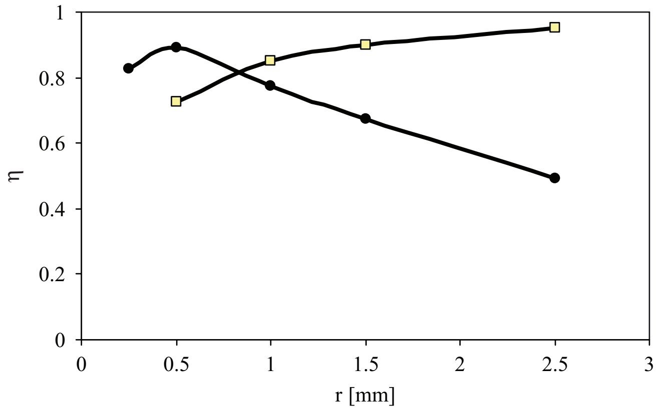

Fig. 9. Notch sensitivity factor versus radius of notch root. (□, $N = 2\times10^6$ impacts, ●, $N = 7\times10^4$ impacts).

For our case β was defined as

$$\beta = \frac{\text{Energy } E_0 \text{ for } r = 3.2\text{ mm at } N \text{ impacts}}{\text{Energy } E_0 \text{ of notched specimen at } N \text{ impacts}}. \tag{3}$$

Two cases were considered: $N = 7 \times 10^4$ impacts and $N = 2 \times 10^6$ impacts.

Analyzing Fig. 9 two conclusions could be pointed out:

- Different behaviours of the notch sensitivity factor η versus r for the two considered numbers of cycles emphasize the particular character of damage at repeated impacts in the limited durability domain.
- The similar behaviour of η at impact fatigue with high number of cycles ($N = 2 \times 10^6$ impacts) with the non-impact fatigue.

These conclusions confirmed that once the number of impacts to fracture increase at the impact fatigue tests the results are similarly with those obtained for classic fatigue tests.

3.4. Fracture analysis

Torsional static tests, single impact tests and repeated impact tests show that the fracture surface in the stress concentration region has different aspects. In the case of the torsional static tests and single impact tests the fractures were produced in a plane normal to the longitudinal axis of the shaft, underlying the important role of tangential stresses. The fracture at repeated impacts shows the contribution of the maximum normal stress. The surface crack propagation, under repeated torsional impacts, is shown in Fig. 10. The crack is initiated at the section change from square to circular; it propagates at the angle θ with the cross-section plane similarly with the path observed by Yang and Kuang [12] for torsional non-impact fatigue test. The crack propagation path is obtained by measuring the horizontal increment Δx and the vertical increment Δy. The crack extension angle θ can be obtained from (Fig. 11)

$$\theta = \arctan \frac{\Delta x}{\Delta y}. \tag{4}$$

An average value of 48.6° was obtained for the crack propagation angle.

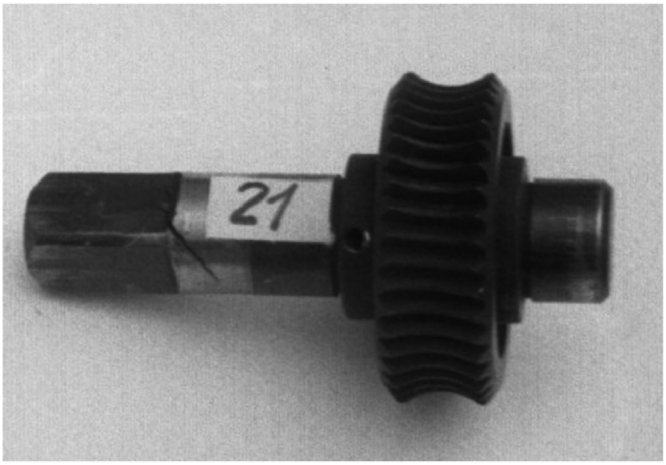

Fig. 10. Cracked shaft under torsional impact fatigue.

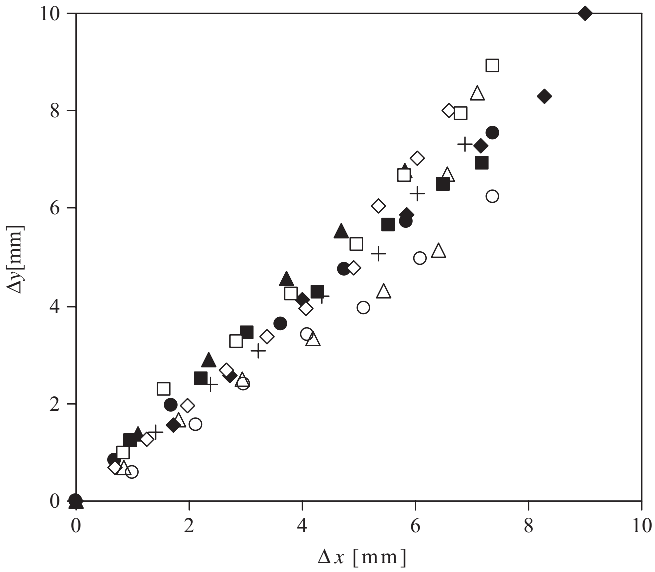

Fig. 11. The crack propagation path under impact fatigue torsion (◆, specimen 5; ▲, specimen 21; ■, specimen 22; ○, specimen 24; ◇, specimen 26; □, specimen 27; ●, specimen 28; +, specimen 29; △, specimen 31).

4. Conclusions

The paper presents a methodology for studying the fatigue strength at repeated impacts for a small dimension shaft. The equipment for repeated impacts was adjusted to implement torsion tests of shafts under the same loading conditions as in service. The stress concentration effect, produced by the fillet radius between square and circular cross-sections of the axle, was emphasized. Five groups of shafts with radius between 0.5 and 3.2 mm from 100 shafts with different notch radii were selected.

The torsional impact fatigue tests were used to obtain the fatigue life E_0-N plots for five considered radii. Based on a model, proposed by the authors to determine the energy reduction factor due to notch β, the variation of the notch sensitivity factor η versus fillet radius was analyzed for two different numbers of cycles. It was observed that for a high number of cycles ($N = 2 \times 10^6$ impacts) the behaviour is similar to those in the case of classic fatigue tests. Conversely, at a lower number of cycles the particular aspect of the notch sensitivity in the limited durability domain is highlighted. Under torsional impact fatigue, the crack propagation direction at the surface of the specimen was almost constant with an angle θ approximately 48.6°.

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