FATIGUE LIFE OF FORGED, HARDENED AND TEMPERED CARBON STEEL WITH AND WITOUT NORMALIZING

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ABSTRACT
A common process of auto-parts production consists of forging, normalizing, quench and tempering. Normalizing treatment is usually employed to improve machinability of steel, and to homogenize and refine the microstructure. For simple parts, production cost would reduce if normalizing stage were eliminated. In this paper, effects of normalizing on properties of a carbon steel has been studied. Experiments have been carried out at industrial conditions on forged, quenched and tempered parts. Results show minor effect of normalizing on microstructure, hardness and tensile properties. However, specimens normalized after forging indicate improved fatigue life at different stress amplitudes. Forty samples were tested for each heat treatment at three different stress amplitudes. Statistical analysis of the results proves meaningful reduction in number of cycles to failure for specimens without normalizing treatment. It is believed that more number of cracks in these specimens and more coalescence of cracks cause the early failure of specimens. Disperse ferrite areas in microstructure seem to be the preferred initiation sites and different distribution of ferrite in the microstructure of samples leads to different fatigue lives.

Keywords: fatigue life, heat treatment, normalizing, microstructure and carbon steel.

1. INTRODUCTION

Forging the steel parts followed by heat treatment is a common process in auto-part manufacturing. The heat treatment involves normalizing, austenitizing, quenching and tempering. Normalizing treatment before hardening is mainly for homogenization and refinement of microstructure and softening the steel. Homogenization and microstructure refinement improve mechanical properties and prevent distortion or cracking of parts with complicated shapes during hardening, while softening reduces machining costs. If the part does not need machining, and has a simple shape, normalizing treatment may be eliminated from the process to decrease manufacturing costs. For this decision, the effect of normalizing on the mechanical properties of the part should be considered. It is the aim of this paper to investigate these effects on mechanical properties of a carbon steel, with an emphasis on the fatigue life of the parts.

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2. EXPERIMENTAL PROCEDURE

The part selected for this study is a ball pin made of CK45 steel (see table 1). Steel bars with 38 millimeter diameter cut in 250 millimeter pieces were heated to 1250°C in an induction furnace and forged in two steps by a 1000 ton mechanical press. 120 forged parts were selected, from which, 60 parts were normalized and all 120 parts were hardened and tempered altogether. Normalizing took place at 890°C for 130 minutes and cooled in air. All parts were austenitized at 890°C for 120 minutes and quenched in oil and then tempered at 570°C for 75 minutes. All treatments were followed based on manufacturing procedures at industrial conditions.

Table 1. Chemical composition of CK45 steel.

Elements	C	Si	Mn	P	S	Cr	Ni	Mo
Wt%	0.44	0.22	0.64	0.006	0.012	0.15	0.11	0.05

Hardness of all parts was measured. One metallographic sample was taken after each treatment. For the purpose of simple reference, abbreviated name for each condition is listed in table 2. Tensile properties were determined according to ASTM E8m for two QT and two NQT samples using a 200kN universal testing machine. Prior austenite grain size was measured for specimens based on ASTM E112, using a quantitative image processing software (MIP*).

Table 2. Treatment condition of samples

	Condition	**Abbreviated Name**
1	As received	AR
2	As forged	AF
3	Forged and normalized	N
4	Forged and hardened (quenched)	Q
5	Forged, normalized and hardened (quenched)	NQ
6	Forged, hardened and tempered	QT
7	Forged, normalized, hardened and tempered	NQT

Fatigue tests were carried out for twenty QT and twenty NQT samples using a rotary bending fatigue testing machine. A drawing of fatigue test piece is shown in figure 1. Fatigue test pieces were made from parts with hardness between 60.2 to 61.4 HRA. The test pieces were machined with a CNC machine and grinded with silicon carbide paper grades 400, 600, 1000 and 2500 and finally polished to a bright surface with one micron diamond paste.

RESULTS AND DISCUSSION

Hardness of samples after each treatment is given in table 3. Hardness numbers are the average value of five readings on each part. The difference between parts hardened with and without normalizing (NQ and Q) is about 0.7HRA while after tempering (QT and NQT) the difference reduces to about 0.1HRA. However, the hardness measurement taken on all QT and NQT parts shows wider range of hardness values. A T-test† was performed on 96 samples to show any significant difference between the two sets of parts. This test confirms NQT samples with an average hardness of 61.45HRA are harder than NQT with an average hardness of 60.31HRA. Although this difference in hardness is very small compared with

* MIP is a registered trade mark metallographic image processing software developed at Ferdowsi University of Mashad.

† Student T-test or paired variance test

acceptable range for hardness of these parts and does not represent a significant change in mechanical properties, it confirms a difference resulted from normalizing treatment.

The prior austenite grain size of samples after each treatment is given in table 4. Figures 2 to 11 show the microstructure of different samples. Small changes of prior austenite grain size and little differences in microstructure of QT and NQT sample are observed. Therefore, it is expected to see little changes in mechanical properties as well. This is true for tensile properties as summarized in table 5.

Table 3. Average hardness at different condition.

Condition	AR	AF	N	Q	NQ	QT	NQT
Average hardness (HRA)	58.04	58.44	54.68	62.92	62.22	61.78	61.88

Table 4. Prior austenite grain size, ASTM E112.

Condition	AR	AF	N	Q	NQ	QT	NQT
Prior austenite grain size	9.2	9.3	9.4	9.9	9.6	10	10.3

Table 5. Tensile properties of two QT and twoNQT samples.

Specimen number	**Yield Stress N/mm^2**	**Tensile Strength N/mm^2**	**Elongation %**
QT-1	584	861	17.7
QT-2	578	851	16.7
NQT-1	584	850	17.2
NQT-2	588	844	16.7

S-N curve is drawn for QT and NQT samples in figure 12 and table 6 summarizes the fatigue test results. From figure 12 the difference between the lives of QT and NQT samples is evident. Nevertheless, in order to see the statistical significance of this difference and to assure the changes of average lives at different stress levels do not lie within the normal variations common to fatigue testing results, T-test was performed on the fatigue lives.

Table 6. Fatigue test results.

Condition	**Stress Amplitude MPa**	**Number of Tests**	**Average Life**	**Standard Deviation**	**Average Number of Cracks***
QT	583	8	45635	15181	17.3
QT	534	8	101399	27881	N/A
QT	516	4	137837	48125	9.7
QT	Normalized for 583	20	45635	14775	
NQT	583	8	54018	11184	11
NQT	534	6	119552	37531	8.5
NQT	516	6	194089	68817	5.6
NQT	Normalized for 583	20	54635	13528	

* Average number of cracks counted on the fracture surface.

The results of T-test at each stress level did not confirm a significant difference between average lives of QT and NQT samples (see table 7). On the other hand, in all three stress levels similar difference is distinguished, as average lives of QT samples in all three stress levels are shorter than those of NQT samples. Since the purpose of using T-test is to differentiate between QT and NQT conditions in general, a normalizing formula was employed to test fatigue data altogether. For this, average fatigue life at 583MPa was taken as a reference value, and the lives of samples tested at 534 and 516MPa were divided by the ratio of their average life to the reference value. In this way, normalized lives of twenty QT samples and twenty NQT samples were used for T-test. The results given in table 7, verify significant change in average life of the QT samples over that of the NQT specimens.

Table 7. Two-Sample T-Test and CI: NQT, QT

Stress Amplitude	T-test Results
583 MPa	**Estimate for difference**: 8383.75 **95% CI for difference**: (-6141.46, 22908.96) **T-Test of difference** = 0 (vs not =): **T-Value** = 1.26 **P-Value** = 0.232 DF = 12
534 MPa	**Estimate for difference**: 18152.8 **95% CI for difference**: (-23860.3, 60165.9) **T-Test of difference** = 0 (vs not =): **T-Value** = 1.00 **P-Value** = 0.348 DF = 8
516 MPa	**Estimate for difference**: 56252.2 **95% CI for difference**: (-31216.1, 143720.4) **T-Test of difference** = 0 (vs not =): **T-Value** = 1.52 **P-Value** = 0.172 DF = 7
Normalized for 583 MPa	**Estimate for difference**: 8383.75 **95% CI for difference**: (-692.30, 17459.80) **T-Test of difference** = 0 (vs not =): **T-Value** =1.87 **P-Value** = 0.069 DF = 37

Fracture surfaces of all samples were examined with the aid of a stereomicroscope. Figures 13 and 14 show typical fracture surfaces of two samples tested at 583 MPa. Number of cracks on the final fracture surface of each sample was counted (see table 6). Average number of cracks increases as the stress amplitude increases. At the same stress amplitude the average number of cracks is higher for QT specimens. Examination of the specimen surfaces for cracks other than those on the final fracture surface agrees with the fact that the number of cracks which could be detected on the surface of QT specimens is larger than that of NQT specimens. More number of cracks initiated in QT samples followed by coalescence reduces the life of QT samples compared with those of NQT specimens. This can be related to more preferable crack initiation sites in QT samples. It is well established that ferrite is the usually the crack initiation site in ferritic-pearlitic steels[1-4]. Many researchers have shown that ferrite grains in ferritic-pearlitic steels[5-8] and even in duplex steels[9-10] are the favorable sites for crack nucleation. G.Z. Kovalchak, et. al. [6] reported reduction in fatigue life with increase of ferrite in microstructure. In QT samples more disperse ferrite areas could very well be the reason for the more number of cracks and the shorter lives. Homogenized microstructure of normalized samples (NQT) seems to be less vulnerable to crack initiation and results in longer lives. Estimated ferrite in QT samples is about 12-15% while 7-10% ferrite is observed in NQT samples. This reasonably explain the difference in lives of the two sets of samples.

SUMMARY AND CONCLUSIONS

A number of experiments at industrial conditions were conducted to investigate the effects of normalizing treatment on mechanical properties of auto parts which were forged, hardened and tempered. The results show elimination of normalizing treatment has little effect on hardness and microstructure of simple parts made of medium carbon steel and does not change the tensile properties. However, meaningful changes of fatigue life at medium cycle are recognized. Samples made from parts without normalizing treatment show shorter lives and more number of cracks in fatigued specimens. More number of cracks on the surface and fracture surface of QT samples seems to be the reason for shorter lives of these specimens. Based on microstructural examination it is assumed that more disperse ferrite grains in QT samples are the cause of more crack initiation and more coalescence in these samples lead to shorter lives. More detailed experimental work is needed to examine the crack initiation area and to investigate the effect of normalizing on reducing the number of cracks in forged, hardened and tempered carbon steels.

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Figures

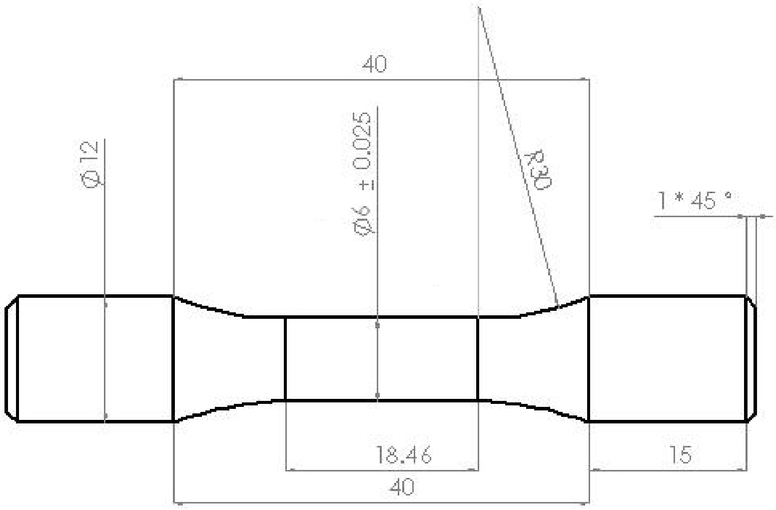

Figure 1. Drawing of fatigue test specimen

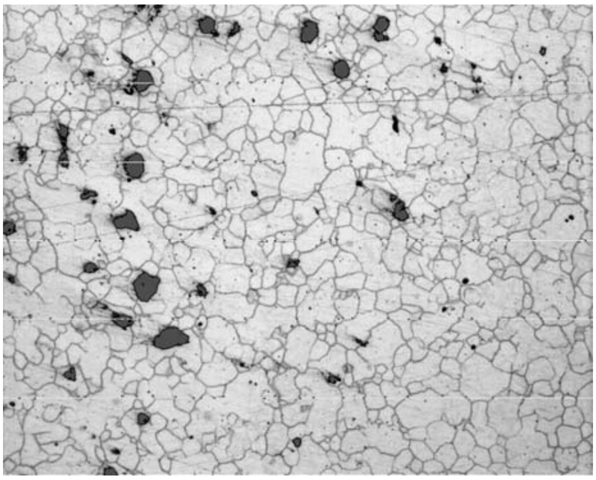

Fig. 2. Prior austenite grains of quenched and tempered (QT) sample.

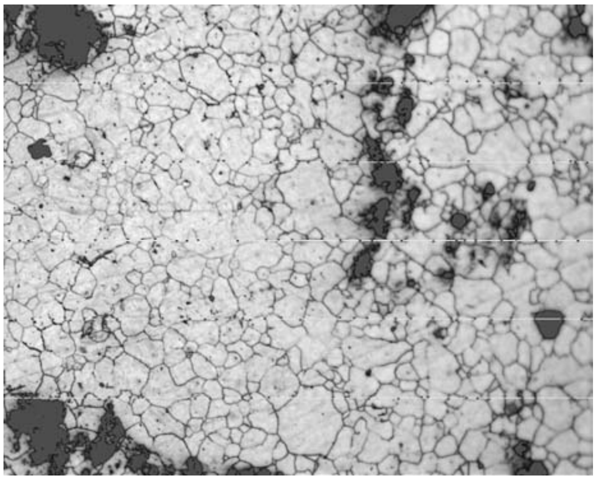

Fig. 3. Prior austenite grains of normalized, quenched and tempered (NQT) sample.

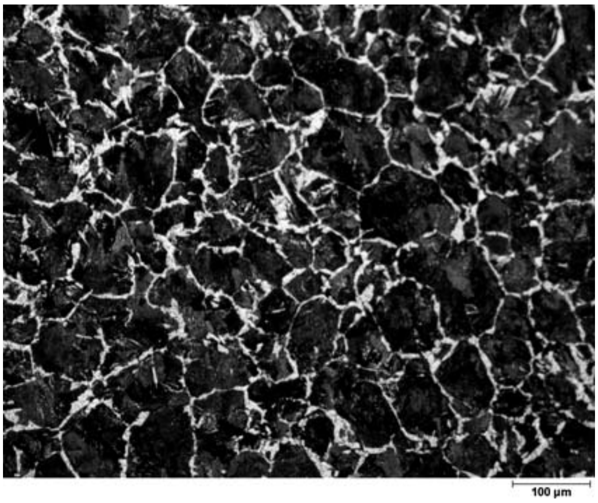

Fig. 4. Microstructure of as forged (AF) sample. (100X)

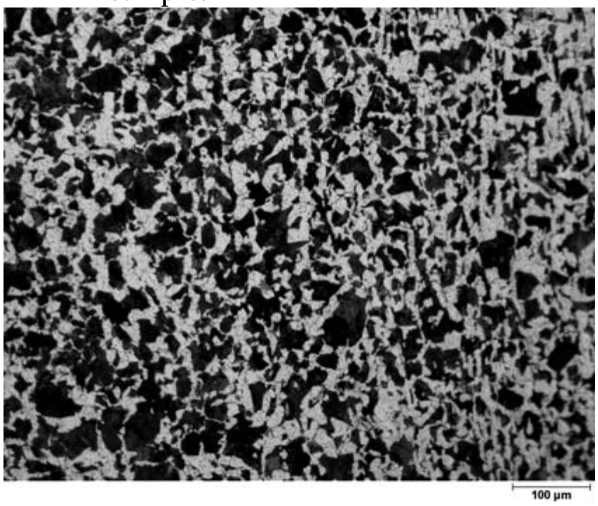

Fig. 5. Microstructure of as forged and normalized (N) sample.

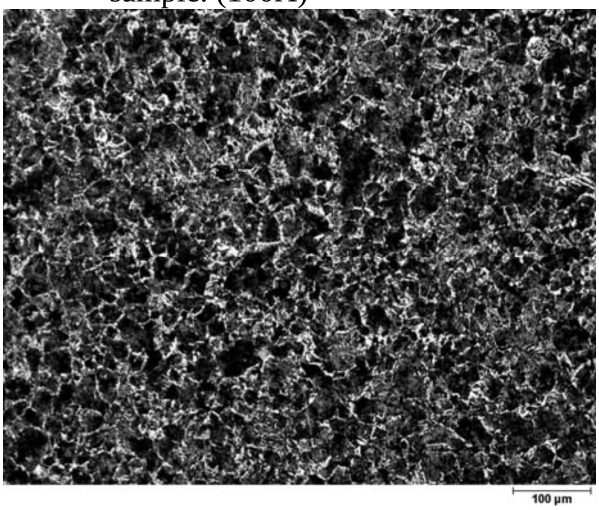

Fig. 6. Microstructure of forged, quenched and tempered (QT) sample. (100X)

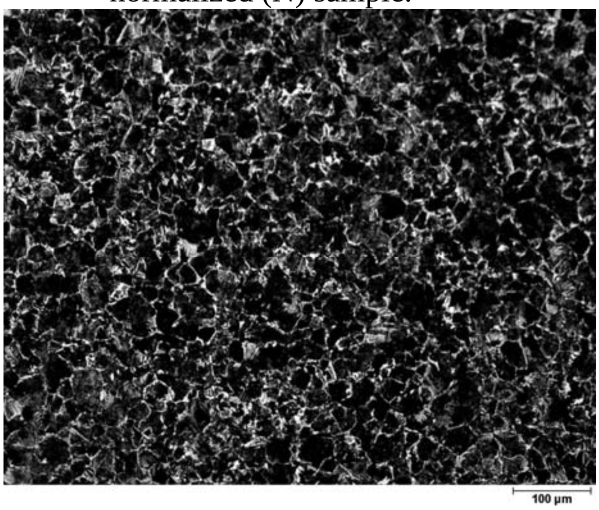

Fig. 7. Microstructure of forged, normalized, quenched and tempered (NQT) sample. (100X)

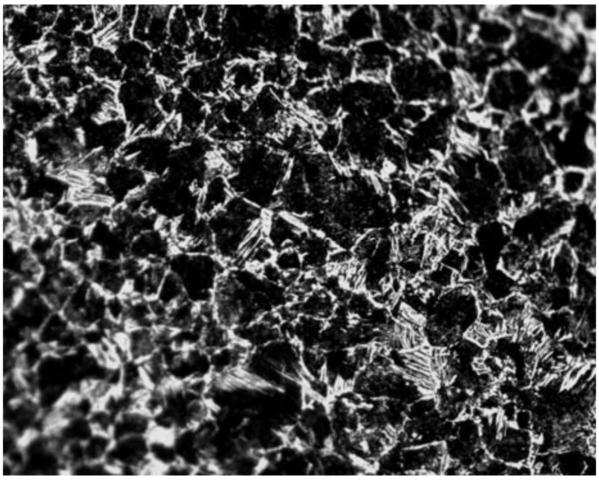

Fig. 8. Microstructure of forged, quenched and tempered (QT) sample. (200X)

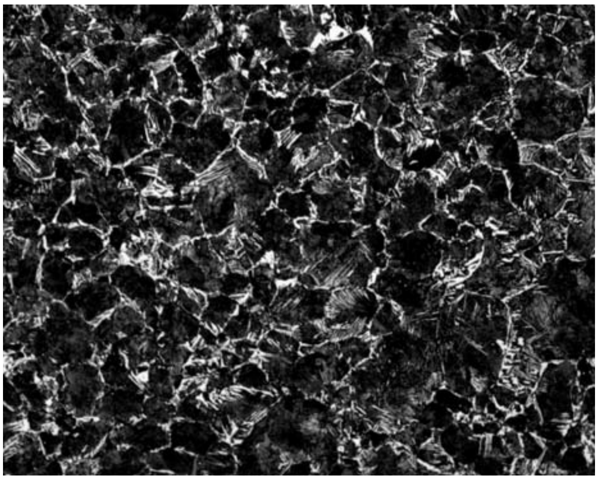

Fig. 9. Microstructure of forged, normalized, quenched and tempered (NQT) sample. (200X)

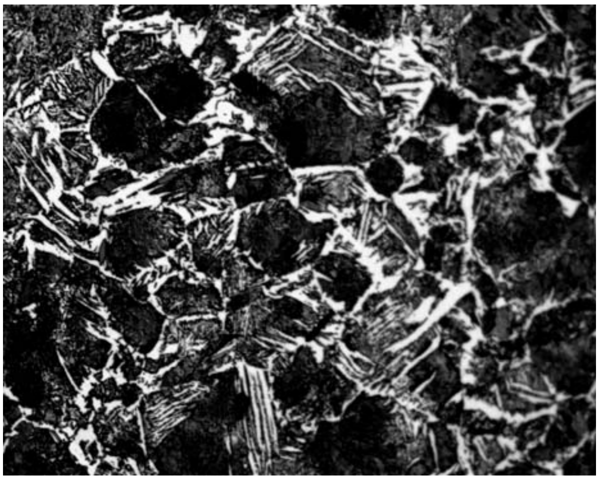

Fig. 10. Microstructure of forged, quenched and tempered (QT) sample. (500X)

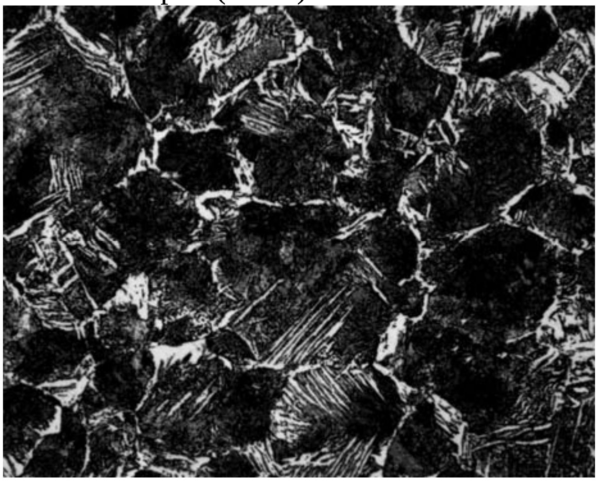

Fig. 11. Microstructure of forged, normalized, quenched and tempered (NQT) sample. (500X)

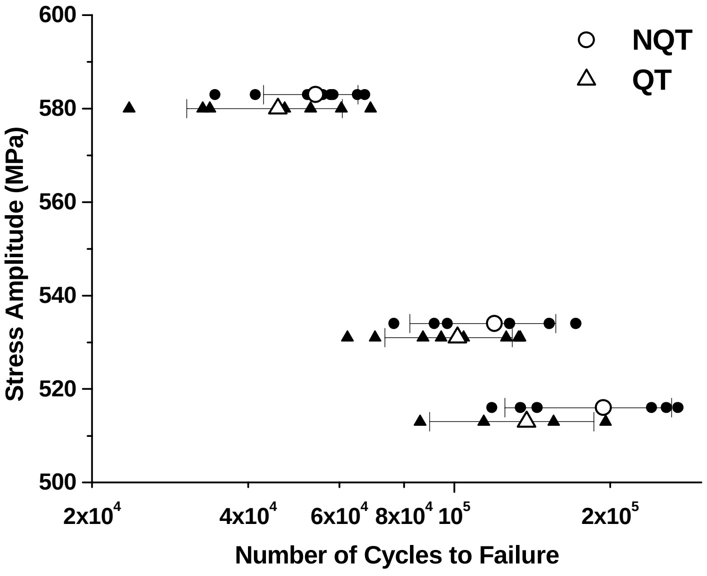

Fig. 12. S-N curve for QT and NQT samples.

Fig. 13. Fracture surface of QT sample.

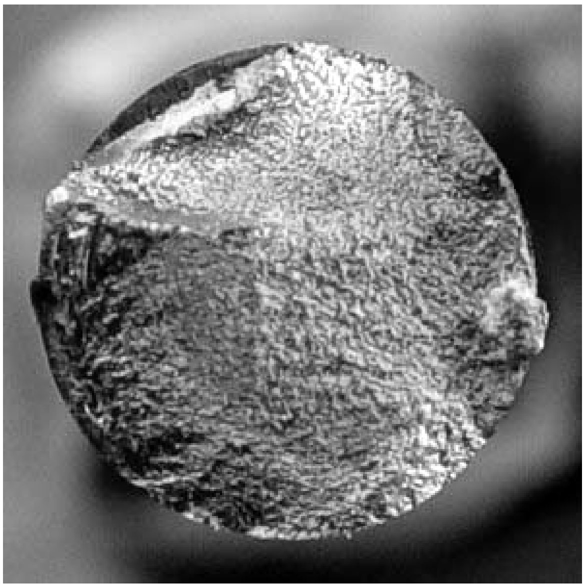

Fig. 14. Fracture surface of NQT sample.