FATIGUE DAMAGE ACCUMULATION UNDER VARIABLE LOAD CONDITIONS.

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The mechanisms of crack initiation during cyclic loading of Cu specimens under variable load conditions were studied. It was observed that, for the conditions used in this work, the crack initiation mode depended strongly on the load level and on the sequence of the applied cyclic load. The effect of the removal of a thin surface layer was also investigated.

The results obtained were analyzed in terms of fatigue damage accumulation.

INTRODUCTION

The assesment of fatigue life under variable load conditions remains largely an unsolved technological problem. Miner's rule, extensively used in fatigue design, fails to describe correctly the behaviour of materials under these conditions and all the alternative criteria developed up to date have proved to do so only under restricted conditions. The fracture mechanics approach has been useful in describing the propagation of a relatively long predominant crack, but the analysis of materials having initially undamaged surfaces (at least from a macroscopic point of view) is much more complex. In this case, the mechanisms of crack initiation and propagation must be considered. In the case of cumulative fatigue damage under variable loads particular attention should be payed to the magnitude and sequence of the applied loads.

It is well known(1) that for specimens cycled under constant stress or strain conditions, the crack initiation and propagation modes depend on the dislocation structures developed during the fatigue process. For high stresses (or strains) a cell structure developes under fatigue conditions while at intermediate and low stresses a mixture of walls (characteristic of persistent slip bands or PSB's) and matrix structures is formed. PSB's are responsible for high strain concentrations (2,3) within the polycrystal grains which promotes a transgranular crack initiation mode (4).

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At high stresses the cell structure produces a more homogeneous distribution of strain and an intergranular fracture mode is favoured. Under variable load conditions, interaction and/or superposition effects can be expected between these two fracture modes. A good understanding of these phenomena is necessary to predict fatigue damage accumulation.

This work is a part of a wider research project having the purpose of studying the initiation and propagation of cracks under variable load in a variety of materials and experimental conditions. Crack initiation processes have received considerably less attention in the past as compared to crack propagation so that it's study is a priority in this project.

We report here the results of crack initiation observations performed in Cu polycrystalline fatigue specimens cycled both under constant and variable load conditions. The effect of intermediate repolishing has also been investigated. This last kind of tests have shown, in the past, to yield important information on the damage accumulation mechanisms.

EXPERIMENTAL PROCEDURES

Copper was selected as a material for this work since a lot of information is available on it's fatigue properties. Electrolytic Cu bars with a 13mm x 3mm cross-section were used. A hole 4mm in diameter was machined as shown in Fig. 1. and served as a stress concentrator facilitating the surface observations. The theoretical stress concentration factor so obtained is $K_t = 2.25$. Two sets of specimens were prepaired, a) annealed at 350 C in vacuum for 2 hours and b) as machined. Prior to fatigue testing the specimens were electropolished in a 50% phosphoric acid-water solution. Push-pull fatigue tests with zero mean stress were performed in a servohydraulic machine under load control conditions. A high (H) and a low (L) level was selected for each set of specimens. These were H= 3000 N and L= 2000N for the annealed specimens and H= 4500 and L= 2500 N for the as-machined specimens. Preliminary tests indicated that those loading conditions produced markedly different fracture modes under constant load conditions combined with convenient numbers of cycles to failure. The average number of cycles to failure, N, for the H and L load levels above mentioned were $N_H = 11480$ cycles and $N_L = 134886$ cycles for the annealed specimens and $N_H = 21232$ cycles and $N_L = 282834$ cycles for the as machined specimens.

Constant load and two-load-levels tests were performed. In the later, a specimen was initially fatigued at either the H or L level for a number of cycles n_1 after which the test was continued at the other load level. After a number n_2 of cycles at that load level failure occurs. Using the convention widely used in the literature these tests were called L-H and H-L depending on wether the L or H levels were the first ones to be applied. At several points the experiments were interrupted and the specimens taken to the scanning electron microscope for surface observations, after which the tests were continued. The SEM observations were made in the interior surface of the hole at the point of maximum stress concentration.

In order to study the effect of surface damage removal, some tests were interrupted after a given number of fatigue cycles and the specimen was electropolished so as to remove a 0.1 mm layer from the surface. After that the fatigue tests were continued.

EXPERIMENTAL RESULTS

Constant load tests

The evolution of surface markings and crack initiation processes were followed in constant load tests at the two load levels for annealed specimens. In both cases, profuse surface markings were noticed early in the fatigue life. The characteristics and posterior evolution of these markings depended on the applied load level. Fig. 2 shows a micrograph of the internal surface of the hole in the maximum stress region for a specimen fatigued during 10% of it's estimated fatigue life at the H level. The strain distribution was relatively homogeneous in most grains. Some grains presented straight slip bands while in others a more irregular ondulated pattern could be seen. Many grains presented indications of multiple slip. Microcracks initiated at intergranular sites quite early in the fatigue life (10-20%). Practically no transgranular cracks were observed. Growth and coalescence of these cracks was observed as fatigue proceeded as shown in Fig. 3 after 60% of the fatigue life. Several cracks were formed in this way, one of them predominating afterwards and producing failure.

Fig. 4 corresponds to a specimen fatigued at the L load level during 60% of its life. The strain distribution is less homogeneous than in the former case and was mainly concentrated in well defined PSB's. Patches of undeformed material were also observed frequently. The first microcracks were observed at approximately 60% of the fatigue life. They were mainly transgranular, nucleating at PSB's, even if a small proportion of intergranular microcracks were observed. Interlinking of these cracks lead, as in the former case, to the formation of several macrocracks, one of them predominating finally.

Variable load tests

Tests of the L-H and H-L type were performed in several specimens. The results concerning fatigue lives are shown in Fig. 5 and are compared with the predictions of the linear damage accumulation law proposed by Miner, i.e.

$$n_1/N_1 + n_2/N_2 = 1$$

where n_1 and n_2 are the number of fatigue cycles at each load level and N_1 and N_2 the number of cycles to failure at those levels. The straight line represents Miner's prediction. In spite of a high dispersion in the experimental results it is observed that the data for the H-L tests are close to the predictions of Miner's rule while the specimens tested in L-H tests present longer lives than expected from that rule.

The evolution of surface damage was also accompanied by SEM during these tests. Fig 6 shows a micrograph corresponding to a sample fatigued during 60% of it's life at the L level and then until near failure at level H (L-H test). As it has been mentioned before, constant load tests at the L level produced a transgranular failure mode. On the other hand, after a L-H tests a predominantely intergranular mode was observed as seen in Fig. 6, so that a change in fracture mode took place when the load was increased from L to H.

Typical results for H-L tests are shown in Fig. 7, corresponding to a sample fatigued during 60% at the H level, after which the load was decreased to L and fatigued to near failure. It can be seen that the intergranular mode characteristic of the H level still persisted after fatiguing for a significant portion of the fatigue life at the L level. Some transgranular cracks were observed but it's proportion was too small to modificate the general intergranular characteristic. In brief, no change in fracture mode could be observed when the load was decreased from H to L in a fatigue test.

Repolishing experiments

The effect of the removal of a thin (0.1 mm) surface layer after a certain number of fatigue cycles, n_1, on the remaining fatigue life at the same or a different level was investigated. Preliminary tests in annealed specimens resulted in a very high dispersion of the experimental results, making it impossible to arrive to definite conclusions with respect to variations in the fatigue life as a result of intermediate repolishing. For that reason, as machined specimens were used in this tests. For these specimens, similar behaviour to that observed for the annealed ones was observed during continuous, H-L and L-H tests provided the appropriate values of H and L loads were used as mentioned in the description of experimental procedures.

Tests with n_1 values corresponding to 10% and 60% of the fatigue lives were performed. Intermediate repolishing had only modest effects on the fatigue lives of the specimens tested. For constant load tests, a small increase of about 10-20% could be observed but in the H-L and L-H tests the meassured values of fatigue lives fell within experimental scatter of the lives corresponding to tests without intermediate repolishing.

Both at the L and H levels, after 60% of the fatigue life cracks had already initiated and, specially at the H level, but also to a great extent at L, microcracks had coalesced. As repolishing removed only a very thin layer, this was not enough to eliminate the surface cracks as can be seen in Fig. 8 for a specimen fatigued during 60% of it's life at the H level and electropolished. This test was continued at the L level for 110500 cycles, corresponding to a fraction of 40% of it's fatigue life at that level. Fig. 9 shows the state of the surface after this process. It can be seen that practically no surface markings appear. A possible explanation for this observation is that the specimen was already in the crack propagation stage and plastic deformation was essentially confined to the surroundings of the crack tip so that nothing can be observed at the surface. This stage is better studied by SEM observations of the fracture surface. Since we are dealing here only with crack initiation, the results concerning this stage will be reported elsewhere. For that reason, only observations made in specimens repolished after 10% of their fatigue lives will be reported here.

a) Constant load tests. Fig. 10 shows the surface of a specimen fatigued at the L level during 10% of it's fatigue life and repolished. No surface markings remained and also no cracks could be observed. After that, the fatigue test was continued until near failure (Fig. 11). Surface markings reappeared, presenting the same characteristics as those prevalent before repolishing. Basinski et al (2) and Pascual and Rolim (5) have reported a finer slip distribution in the PSB's after repolishing. In this case, this effect was only observed in some areas and was not a characteristic feature. The crack initiation mode was transgranular.

Similar results were observed when intermediate repolishing was performed in specimens fatigued at the H level. After repolishing a homogeneous distribution of surface markings reappear, as can be seen in Fig. 12, and a predominantely intergranular crack initiation mode is stablished.

b) Variable load tests. Fig. 13 shows the results obtained for a sample cycled 10% of it's life at the L level, repolished and cycled at the H level to failure (L-H test). After 24000 cycles at the H level slip markings are seen to have reappeared in the surface. They are somehow different from those on constant load H tests (see Fig. 2) in the sense that better defined PSB's appear. The failure mode is a combination of intergranular and transgranular, this last mode being more frequently observed than in the case of L-H tests without repolishing. However, the intergranular crack initiation mode is still predominant.

In the case of H-L tests and after repolishing, a structure quite similar to that corresponding to a constant load test was observed (Fig. 14). The crack initiation mode is predominantely transgranular, contrary to what is observed in H-L tests without repolishing.

DISCUSSION

Surface observations of specimens fatigued under constant load conditions were consistent with the idea that for the H level a dislocation structure composed mainly of cells is formed, while at the L level it must consist of PSB's and matrix structures. In this later case the structure consist of a combination of "hard" (matrix) and "soft" (PSB's) materials which produces a high concentration of strain in the PSB's and therefore promotes a transgranular mode of crack initiation at the L level. The cell structure generated at the H level permits a more homogeneous distribution of slip and an intergranular crack initiation is observed under constant load conditions.

It is to be expected then, that if the load level is changed during a test, the dislocation structure could change also following the new stress conditions and therefore a variation in crack initiation mode could be observed. Very little work has been done in this area. Pascual and Rolim (5) have shown that matrix to PSB's and PSB's to cells structures transformations are possible even under constant load conditions. Under conditions of variable stress, Figueroa and Laird (6) have reported TEM observations of dislocation structure transformations during L-H tests of Cu specimens. This can explain the existence of interaction and/or superposition effects in variable load tests.

During the L-H tests a transformation from transgranular (L) to intergranular (H) mode of crack initiation was observed. Damage at the L level consisted on the formation of microcracks due to intense slip localized at PSB's. If the load level is increased, a transformation to a cell structure will take place, so that after saturation conditions are established at the H level, a new damage mechanism predominates consisting in the initiation of microcracks in grain boundaries. In an oversimplified approach it could be argued that the damage produced at the L level is "frozen", not contributing to the failure process so that the situation after the stress increase is essentially the same as in the constant load testing of a virgin specimen at the H level in which also a cell structure is formed. In that case, values of n_2/N_2 (fraction of life at the H level) equal or close to 1 must be observed. As can be seen in Fig. 5, the observed values for n_2/N_2 are quite high (0.6 to 0.9) but always less than unity. Several reasons exist to explain that behaviour. In the first place, even if a complete transformation to a cell structure occurs on increasing the stress level from L to H, the structure that developes could be not exactly the same as the one formed in a virgin crystal for the same load level since the histories of both specimens are different. Also, and depending on the value of the stress at the H level, transformation to a cell structure could be only partial so that some proportion of the strain could still be accomodated by PSB's and a mixed mode of crack initiation would be observed. This could be the case for intermediate H level stresses. In our work, some traces of transgranular crack initiation were observed in L-H tests. Another reason is that, if during fatigue at the L level microcracks have grown into the propagation stage so that the stress concentration factor at the crack tip is sufficiently high, the cracks would continue to grow when the load is increased even if the crack propagation mode may change due to the new imposed conditions. Finally, even if no microcracks have formed at the L level, as would be expected for tests with low values of n_1/N_1 (fraction of life at the L level), other interaction mechanisms can be present. Figueroa and Laird (6) have reported that microcracks can be nucleated at the point of intersection of a persistent slip band and a grain boundary, probably due to the high strain concentration produced by PSB's. At the L level, this process, which these authors called "PSB's impingement mechanism" can generate potential points for intergranular crack initiation that could be activated when the load

is changed to the H level.

In the case of H-L tests, intergranular cracks were predominantely observed so that the crack initiation mode doesn't change on decreasing the stress level from H to L and also, little deviation from Miner's linear rule was observed. As mentioned before, at the H level a cell structure is formed. When decreasing the stress level to L it could be expected a transformation to PSB's characteristic of that stress level. However, a cell to PSB's transformation has never been observed, the starting point for the formation of PSB's being always the matrix structure. If an homogeneous structure is formed at the H level, covering the whole volume of the specimen, no transformation to PSB's can occur on decreasing the stress level so that no change in crack initiation would occur as was observed in the present work. In that case, crack initiation would proceed at the L level by a different mechanism to that operative in a constant load L test and should produce deviations from Miner's rule. However, in the H-L tests the fraction of life spent in crack initiation is small, most of it being spent during the crack propagation stage. The fact that Miner's rule is approximately obeyed in our specimens fatigued in H-L conditions may indicate that in this case the crack propagation rate at the L level is not much affected by prior cycling at the high stress H. Further research in this area is necessary but it is interesting to note that a similar effect has been reported by Murakami et al (7) for a carbon steel in low cycle fatigue conditions for which the crack propagation stage also predominated. They concluded that the crack propagation rate was not affected by prior fatigue history and they found that Miner's rule was satisfied.

The results for intermediate repolishing experiments obtained in the present work were rather unexpected. Little effect on the fatigue lives was observed in our case, contrary to what has been reported by other authors. Among others, Basinski et al (2) have reported increases in fatigue life of Cu singlecrystals of the order of 100% as a consequence of repolishing, while Awatami et al (8) found a marked increase in fatigue life for iron polycrystals in H-L tests but only a moderate increase in L-H tests. Also, Kramer (9) reported substantial increases in fatigue lives for Al-2014, 4130 steel and a titanium alloy. All these tests were performed in constant cross section specimens as opposed to the ones used in the present work which had a hole acting as stress concentrator. The removal of a surface layer has the effect of eliminating at least some part of the damage produced during prior load cycling. This contributes to increase the fatigue life. On the other hand, in the specimens used in this investigation, and because of the stress concentration, the surface layer removed is, in the interior of the hole, the harder region, so that the newly exposed surface is softer than before and fatigue life may tend to decrease. The balance between these two processes will control the overall behaviour of the specimens. In the conditions used in this work, these two contributions seem to approximately compensate each other so that a small effect in the fatigue lives is observed. No studies have been reported on the dislocation structures formed during fatigue cycling in the presence of stress concentrators. However, some hints as to that can be obtained from the repolishing experiments described above. In effect, for the H-L tests a change in crack initiation mode from intergranular to transgranular is observed in tests with intermediate repolishing. This effect was no observed in tests without repolishing. After cycling for a given number of cycles at the H level a cell structure is formed in the outer layer and consequently the crack initiation mode is intergranular. However, the dislocation structure may change as a function of the distance to the surface do to the different plastic strain conditions prevalent in those areas. If the outer layer is removed by repolishing, the new surface layer may have a dislocation structure different to that present in the removed layer and that can explain the change in crack initiation mode. The fact that a change from intergranular to transgranular mode was observed in H-L tests after repolishing can indicate the presence of PSB's in the new outer layer showing in this way the inhomogeneity in dislocation structure distribution.

CONCLUDING REMARKS

It has been shown that the mechanisms of crack initiation depend strongly on the cyclic stress conditions imposed on a fatigue specimen and also on the sequence of the applied cyclic load levels. For the conditions used in this work, an increase in load level produced a change from the transgranular to intergranular mode of crack initiation, while a decrease in cyclic load didn't produce a similar change. This can be correlated with the evolution of the dislocation structures formed during these processes and can explain the observed behaviour for the fatigue lives.

The effect of intermediate repolishing was small under the experimental conditions used in the present work and could reflect the effect of an inhomogeneous stress distribution due to the presence of a stress concentrator.

When comparing our results with those of other authors it becomes clear that fatigue damage accumulation depends strongly on the particular conditions and/or materials used and that it could be dangerous to extrapolate results to other conditions or materials. For example, Figueroa and Laird (6) didn't find transgranular crack initiation in Cu samples fatigued in conditions that could be considered similar to the ones used in this work. Also, repolishing didn't yield in our case the increase in fatigue lives reported by other authors.

It seems to be, then, that a general model on fatigue damage accumulation is not feasible with the present understanding of the phenomena involved so that each particular case should be carefully analyzed.

ACKNOWLEDGEMENTS

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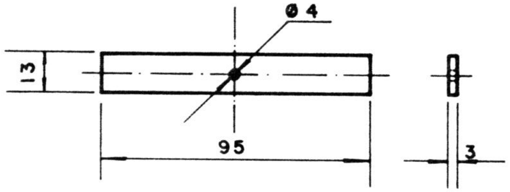

Fig. 1. Geometry and dimensions of the fatigue specimens.

Fig. 2. Constant load test at H level. 10% of estimated life.500x.

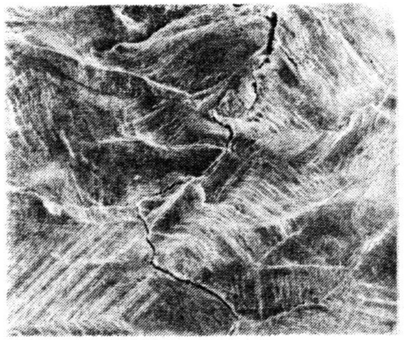

Fig. 3. Constant load test at H. 60% of estimated life.500x.

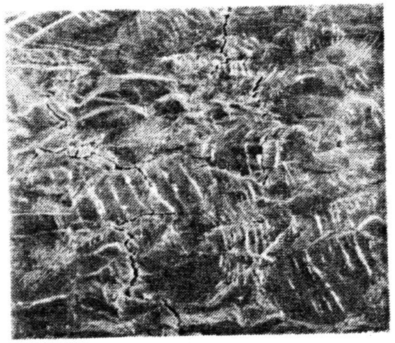

Fig. 4. Contant load test at L. 60% of estimated life. 500x.

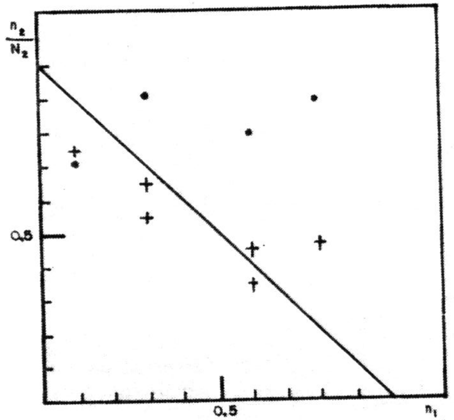

Fig. 5. Fatigue lives for variable load tests.(.) L-H, (+) H-L.

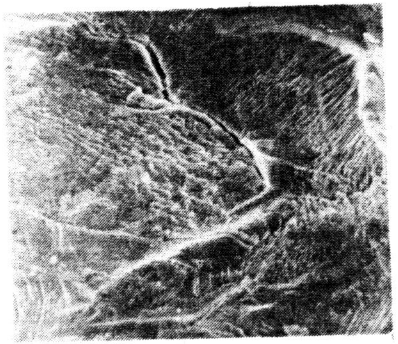

Fig. 6. L-H test. 60% of estimated life at L. 1000x.

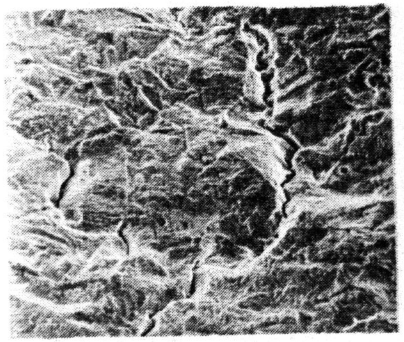

Fig. 7. H-L. test. 60% of estimated life at H. 500x.

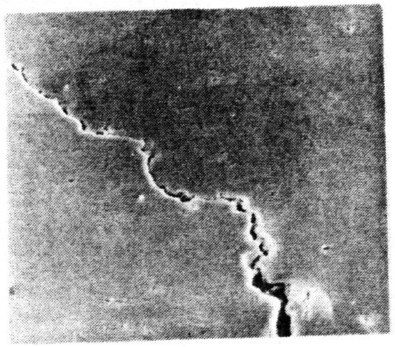

Fig. 8. Specimen fatigued 60% of estimated life at H and electropolished. 1000x.

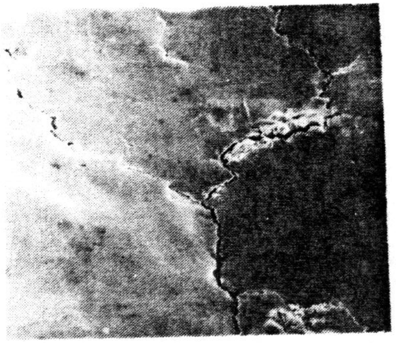

Fig. 9. Same specimen as in Fig.8 after additional 110500 cycles at L. 300x.

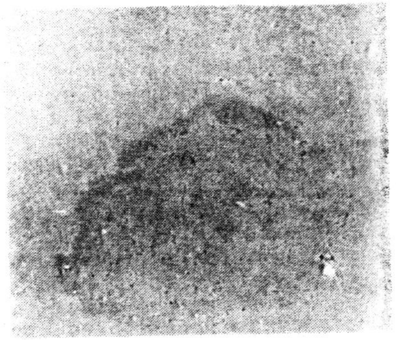

Fig. 10. Specimen fatigued 10% estimated life at L and repolishe 1000x.

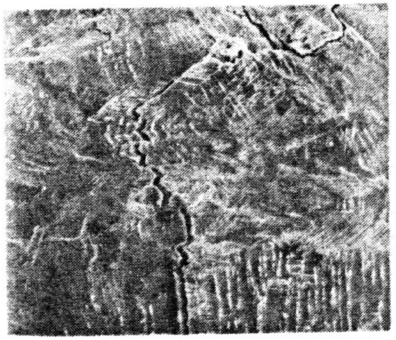

Fig. 11. Same specimen as in Fig.10 after additional cycling at the L level until near failure.500x.

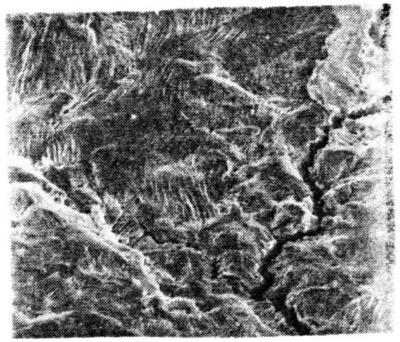

Fig. 12. Constant load test at H with intermediate repolishing. 400x.

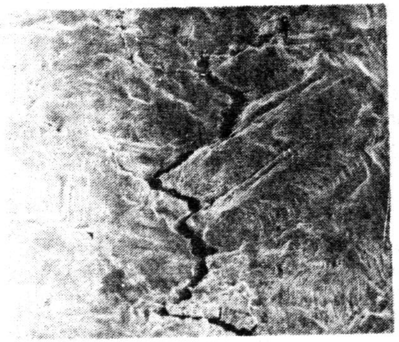

Fig. 13. L-H test with intermediate repolishing. 300x.

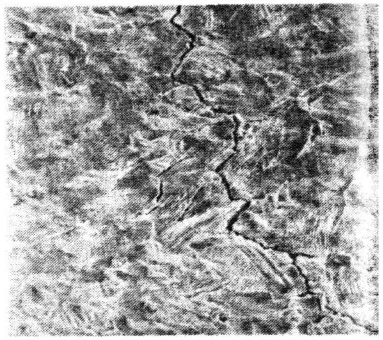

Fig. 14. H-L test with intermedi te repolishing.300x.