Fundamental Aspects of Fatigue Fracture in Plastically Deformed Metals

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The influence of small plastic deformations on fatigue life and fatigue fracture is not unique as can be deduced from literature. It is not clearly understood why some materials increase their fatigue limit due to plastic prestrain whereas others show an opposite effect.

In order to compare fatigue processes in the original and prestrained materials and find differences between them, it is opportune to classify the potentially important factors and elucidate their partial influence on the integral mechanical properties and structural changes. In general plastic deformation manifests itself in

a/ stress-strain curve transformation,
b/ microscopic and macroscopic residual stresses,
c/ microstructural material changes and
d/ secondarily induced effects.

The stress-strain curve transformation together with the macroscopic residual stress influence is depicted in Fig. 1. Here the term "transformation" is devoted to the one-sided extension of the elastic stress range in such a way that its total value equal to $S_{YT} + S_{YC}$ is approximately preserved. If the prestrained specimen is subjected to fatigue loading with a mean stress S_m of the same sign as the prestraining force, the fatigue limit will be higher, because the yield stress increased from S_{YT} to S_{Pl}. For symmetrical or unsymmetrical loading with the opposite sign of S_m this change cannot have a beneficial effect. If the material is repeatedly plastically deformed in both directions due to high peaks of random loading, the stress-strain curve will get permanently transformed. In this case, however, work hardening or softening can play a role and the macroelastic fatigue type of fracture can be replaced by a macroplastic one or evenby cyclic creep with necking.

Macroscopic residual stresses can appear after unloading only when the prestraining force has a gradient caused by a stress concentration or type of loading /bending/. They are superimposed on the external stresses and as a result of their influence and the stress-strain curve transformation /both acting in the same direction/ the original load parameters S_u, S_l and S_m are changed into S_u^{TR}, S_l^{TR} and S_m^{TR}, which in case of Fig. 1 are more favourable from the fatigue viewpoint; the stress amplitude S_a does not, however, alter. Nevertheless, the residual stresses need not be permanent and a few minute lasting resonant vibration can wash them out, as proved by the VSR method.

Tensile or compressive prestrain of unnotched specimens cannot introduce macro-residual stresses, but the fatigue crack initiation can be influenced by an uneven plastic deformation, taking place along the cross section. For a number of reasons the surface layer of one or two grains is deformed to much larger extent compared with the internal volumes and after unloading the self-compensating stress pattern appears; its resulting effect is the same as in the case of macroresidual stresses. Moreover, the heavily deformed surface layer can possess sources of microcracks /around inclusions/, which can reduce fatigue properties.

The most complicated and decisive area in this respect are microstructural changes linked up with macroplatic deformation. Not only can the microstructure of various metals respond in its own way, but the accumulation of fatigue damage can also progress differently. Under these circumstances one is forced to create a certain hypothesis of influence of plastic deformation on microstructure and experimentally examine how the consequent fatigue damage accumulation differs in various sorts of annealed and deformed metals.

Appearance of plastic deformation in microstructure

The microstructural investigation of four sorts of a material, viz. iron, low carbon steel /o.13%C/, copper and 18/8 stainless steel, revealed that surfaces of electrolytically polished and deformed specimens show a marked dependence on heat treatment and rate of cooling as well as on the degree of plastic deformation.

When the material was annealed at high temperature /for low carbon steels above A_{C3}/ and slowly cooled, the onset of plastic deformation is concentrated around grain boundaries, which are made mobile: they slide, slip lines are generated in the area adjacent to them and some of them become corrugated. The grains as a whole move and rotate up to a certain degree of deformation, on exceeding of which they get locked up; a further deformation is accomodated in the grain matrix where slip lines appear and multiply.

If, however, the material is rapidly cooled from high temperature or annealed at low temperature, foreign atoms are stopped to precipitate to the grain boundaries. At the beginning of plastic deformation they therefore either do not move at all or move to a much lesser extent. Consequently, in the first instance slip lines in the matrix appear and grain boundaries move at higher deformations only.

It is to be hoped that the following sketches will at least partially illustrate differences claimed here. Fig. 2a represents the polished and unetched surface of a copper specimen heated at 600°C/1 hour, rapidly cooled and deformed at $\varepsilon = 4\ \%$. The grain boundaries are almost invisible but the originally flat surface is corrugated. A higher deformation emphasizes the grain boundaries, which appear as sharp dark lines, similarly as after furnace cooling /Fig. 2b/; the whole surface is flatter, probably due to better grain accomodation.

Polished and unetched surfaces of 18/8 stainless steel specimens, annealed at 1150°C/1/2 hour, showed the following features:

a/ In the rapidly cooled specimens a small plastic deformation creates slip lines of two systems. The grain boundaries become visible because slip systems of different orientations meet there. When the deformation increases the whole grains move and the surface becomes corrugated. If, however, the rapid cooling is followed by annealing at 700°C/2 hours the double slip systems is still marked but the surface is not so distorted. An increase of annealing time up to 50 hours causes that slip lines originate at grain boundaries, which at the same time become corrugated /Fig. 3a - $\mathcal{E}$ = 9,5 %/.

b/ In furnace cooled specimens plastic deformation emphasizes grain boundaries similarly as in copper. But the following two hour annealing at 700°C suppressed again this ability and material behaves much in the same way as after rapid cooling.

The described differences in microstructural appearance of plastically deformed, slowly and rapidly cooled, high temperature annealed specimens are especially marked in iron. Here the preferable deformation of grain boundary areas after slow cooling is clearly seen as dark valleys /Fig. 3b/, whereas after rapid cooling there are practically no signs of any deformation up to 10 %.

Fatigue damage in plastically deformed microstructure

Manifold microstructural changes condition an unequal material response and damage accumulation under repeated loading. If the material is partially damaged because the plastic deformation created microcracks, the fatigue limit will be lowered. If, on the other side, it work hardens, fatigue properties will be improved. Since grain boundaries contain as a rule a brittle phase /cementite, pearlite/ and inclusions, the grain boundary movement will produce microdamage: the fatigue crack can then become intergranular. Such materials should not be slowly cooled from high temperature. The opposite result means that deformation of the homogeneous matrix /and also homogenous grain boundaries/ is favourable and so the quenched materials increase their fatigue properties due to plastic deformation. This conclusion has been proved by a number of S/N curves obtained for various materials, heat treatment and the ammount of prestrain. One can, however, find some experimental results which do not conform to this hypothesis. The

main divergencies are due to a/ Zener´s mechanism, which can open the microcrack at the grain boundary when slip lines in the matrix appear; b/ the size of grains /small grains are relatively stronger and more easily to move as a whole/; c/ the presence of such elements as Cr, Mg, Si and Ni, which form brittle carbides and lower eutectoid concentration, giving a chance for segregational cementite to appear along grain boundaries /slow cooling/ or in slip systems /rapid cooling/; d/ a number of secondarily induced effects such as static and dynamic strain ageing and a change of transition temperature.

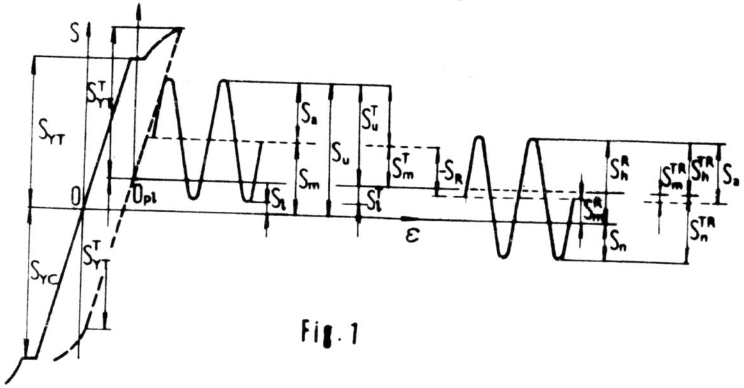

Fig. 1


Fig. 2a


Fig. 2b

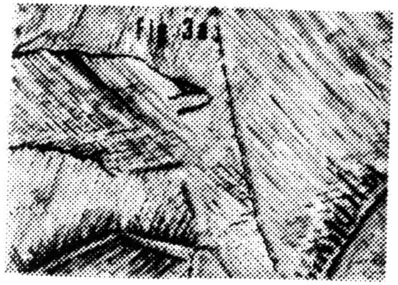
Fig. 3a


Fig. 3b