Plastic Instabilities During Fatigue Cycling

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ABSTRACT

Results are presented from two vastly different experimental investigations which nevertheless exhibited a common feature during fatigue cycling in the form of plastic instability. In the first case a fully killed low carbon industrial structural steel showed intermittent cyclic softening when ± constant stress cycles were applied. In the second case α Cu-Al single crystals were fatigue cycled with constant plastic strain amplitude when a general hardening behaviour was intermittently disrupted with softening. A single explanation is offered for the observed behaviour which seems to hold for both cases and reflects the importance of the mechanical hysteresis. The stress-strain data alone is not adequate for the explanation of the plastic instability and the relationship through the hysteresis loop shape has to be considered for the understanding of the phenomena.

KEYWORDS: fatigue-softening/hardening, plastic instability, hysteresis loop shape, stacking fault energy.

INTRODUCTION

Initially, soft materials generally show hardening under cyclic stressing, while initially hard materials soften until a stable cyclic state is achieved. In the case of steels if the maximum cyclic stress exceeds the yield stress hardening takes place, while initial softening occurs when cycling starts below the yield strength, Klesnil and Lukas (1967). On low carbon steel Klesnil *et al* (1965) reported on the suppression of sharp yield and the disappearance of the Luders strain when cycling for a sufficiently large number of times between the fatigue limit and lower yield stress values. This effect was attributed to the formation of a certain mobile dislocation density in the microplastic range. According to McMahon (1968), dislocation loops expand at such stress levels by long-range motion of large segments providing the free dislocations which may further expand in reversed loading. These ideas were further developed by Abel and Muir (1973b, 1973c, 1975) and some of the obtained results are presented below for the purpose of novel interpretation.

Fatigue experiments on single crystals of Cu and Cu-Al alloys showed that under certain conditions plastic instability can occur, Neumann (1967, 1968), Desvaux (1970). An extensive work on Cu single crystals by Abel (1978) did not lead to the same observation but Abel *et al* (1979a, 1979b) showed that as the Al content is increased in the Cu single crystal from approximately 7 at % the plastic instability is more and more frequent. Some of the results are presented below so that the new interpretation could be extended to these alloys also.

RESULTS

A. Low Carbon Steel

Fully-killed low carbon steel speciments were used with the following chemical composition in percentage: 0.17C, 0.78Mn, 0.24 Si, 0.01P, 0.017S and 0.0085N. The testing arrangement is illustrated in Fig 1 where the specimen dimensions were 9mm and 3mm for gauge length and diameter respectively. Typical test results in the form of stress-strain response after cycling are shown in Fig 2 and the development of plastic strain amplitude for Test No. 3 is illustrated in Fig 3.

B. Cu-Al Alloys

A large number of tests were conducted on single crystals of Cu and α Cu-A1 alloys and all of these crystals were grown from seeds by using a modified Bridgman technique. A single slip and nearly identical orientation was achieved in the alloys containing 2,4,7,11 and 16 at % Al.

The crystals were vacuum annealed at 750° for 1 hour and were subsequently electropolished as shown in Fig 4. Constant plastic strain amplitude cycling of a tension-compression type was carried out at room temperature by a Schenk Pulsator with plastic strain control modification using a triangular waveform command signal from a function generator. The load versus number of cycles were continuously recorded on a running chart while individual load extension or hysteresis curves were recorded by an X-Y ploter. A light microscope was mounted over the specimen to monitor slip and crack development.

Typical cyclic hardening curves together with some hysteresis curves for the Cu-4% Al, Cu-11% Al and Cu-16% Al are shown in Figs 5-6-7, respectively. Elongated hysteresis loop shape is presented in Fig 8 and rugged contours of the cyclic hardening curves are illustrated in Figus 9-10.

DISCUSSION

A. Low Carbon Steel

The effect of cycling below the yield strength of low carbon steel is indicated in Fig 2 where it is clear that tensile and reverse cycling lead to very different subsequent responses. Tensile stress cycling may generate enough mobile dislocations at higher stress levels which leads to the disappearance of the sharp yield point, -but at lower cyclic stresses in the microstrain range an exhaustion hardening operates and the yield behaviour may even sharpen up, Abel and Muir (1973b, 1973c). In the case of Figure 2 tensile cycling resulted in a sharp yield.

More concern for the present paper is the way and mechanism of the disappearance of the sharp yield when lower stresses were cyclicly applied in a load reversal manner. What is obvious that these results imply that microyielding effects occur at much lower stress levels than the upper or lower yields and reverse loading generates more and more mobile dislocations as cycling takes place. Concentrating on Test No. 3 as outlined in Fig 3 the first detectable plastic strain appeared to be around 10^{-6} when ± 316 MPa has been cyclicly applied. At approximately 300 cycles the strain amplitude became 10^{-5} and from thereon a peculiar strain response developed with a steady increase of the strain amplitude leading to a strain plateau. Initially, therefore in part or parts of the specimen a deformed region is nucleated in the undeformed matrix forming an embryo or cluster which eventually becomes large enough to propagate across the diameter of the specimen and forms a Luders band. There is no difficulty in accepting the idea of the growth of mobile dislocation density as a result of fully reversed loading with the interply of the Bauschinger effect.

The difficulty arises when cycling is taking place under constant plastic strain amplitude at the plateau region between approximately cycle Nos. 370 and 500 for example. The creation of the Luders band took place under open loop cyclic condition which allowed for the growth of plastic strain amplitude. At the plateau cycling however the machine controls the peak stresses of the hysteresis loop with ± constant load cycling, but relatively suddenly a self-imposed constant ± plastic strain amplitude cycling comes into operation that is the hysteresis loops are closed. This means that cycling takes place within a rectangle with fixed tensile and compressive peak stresses and with fixed plastic strain amplitude. As with further cycling at the end of the plateau, an open-loop situation develops again it is obvious that during the plateau cycling changes must take place which prepare the specimen for the softening event. With fixed peak stresses and fixed plastic strain amplitude the only degree of freedom left relates to the actual shape of the hysteresis loop.

Hysteresis loop shapes can be expressed through the Bauschinger energy parameter, β_E, which is defined on Fig 11, Abel and Muir (1972). Accordingly, when $\beta_E = 0$ the average deformation stress $\bar{\sigma}$ in any one half cycle approximately equals the average frictional stresses $\bar{\sigma}_F$ of that particular half cycle. As β_E has a finite value the average stresses in any one half cycle are made up from the average frictional stresses $\bar{\sigma}_F$, plus the average elastic stresses associated with dislocation interactions: $\bar{\sigma}_E$. Larger is the value of β_E larger is $\bar{\sigma}_E$, that is, larger is the dislocation related elastic stress state. It is therefore proposed that the likely events in this step-wise softening process may be:

1. In the microplastic range, due to the reverse loading, mobile dislocations are created leading to the establishment of a Luders band.

2. In the freshly yielded zone a gradual homogenization of stress and strain takes place leading to a build up in the internal elastic stresses in that zone.

3. Finally, from the confined volume of the specimen a break-out occurs to form a new freshly-yielded zone, that is the Luders band advances.

In constrast to the part played by the Luders band in normal tensile testing, here the reverse loading first destroys the propagational potential of that band and only with repeated reverse loading does the dislocation structural rearrangement develop high elastic interactions. Once this process reaches a critical stage there are two obvious possibilities: cyclic hardening in the yielded zone or the expansion of the yielded zone. Energetically, the latter is favourable and thus step by step the softening is nothing else but the expansion of the plasticly active volume of the specimen. Finally, when this type of "softening" covers the whole of the specimen cyclic hardening is the only possibility left and indeed it does take place.

As a conclusion therefore, it may be stated that the conventional approach of observing stresses and strains alone run into difficulty when explanation is needed for the type of test result presented above. Through the observation of the change in the hysteresis loop shape significant information can be obtained and with the Bauschinger energy parameter one is able to assess the nature of the deformation processes taking place during cycling. More particularly, the balance between the average frictional forces resiting dislocation movement, $\overline{\sigma}_F$, and the developing elastic interaction forces, the average elastic stresses associated with dislocation movement $\overline{\sigma}_E$ give insight to the stability of the deformed state. In this respect, the Bauschinger stress parameter, β_σ, can be also used as an index for the assessment of the stability of the deformed state, Abel and Muir (1972). An increase in the internal elastic stresses which retard the forward movement of dislocations, will initiate plastic flow during reversed loading at a lower applied load so that the stress parameter, $\beta_\sigma = (\sigma_p + \sigma_R)/\sigma_p$, where σ_p is the peak stress and σ_R the reversed yield stress, will increase. These changes associated with the peculiar softening process are illustrated in Fig 12.

B. Cu-Al alloys

In F.C.C. metals it is energetically favourable for dislocations to dissociate into two partial dislocations separated by a stacking fault. The equilibrium separation of the partials is determined by the stacking fault energy (s.f.e.). Cross slipping of partial dislocations is difficult it they are widely separated as is the case in materials of low s.f.e. The stacking fault energies of alloys of the Cu-Al system have been studied by a number of investigators and according to Smallman and Green (1969) within the α Cu-Al range the s.f.e. decreases from 70 erg/cm^2 for pure Cu to about 2 erg/cm^2 at 16 atomic % of Al content. This significant variation in the value of s.f.e. suggests a significant variation in the cyclic properties of these alloys, and the investigation was centred upon this aspect.

The Cu, Cu-2Al and Cu-4Al crystals showed a very similar behaviour which is illustrated in Fig 5. However, once the Al content reached 7 at % the cyclic hardening curves changed in character as shown in Figs 6-7. A continuous hardening envelope develops with cycling accompanied with some degree of ruggedness at the contour, Figs 9-10.

Initially, this ruggedness gave concern about the behaviour of the testing equipment, but with further testing it became obvious that it happens only with the low s.f.e. crystals. Thus, great effort was made to give explanation to the peculiar phenomenon and eventually it was discovered that at a significant stress disturbance in fact a plastic strain instability occured as shown in Figs 13-15. Consider in Figure 13 cycle No. 16400 where the loop shape is quite pointed with a large β_E value. At that stage, the dislocation structure, due to the short range order and other pinning effects together with the prevailing s.f.e. reached a critical stage so that new mobility was needed. Note the pointed nature at the peak stress. Thus in cycle No. 16401 a strain burst occured at the peak stress level at such a large intensity that the machine, with plastic strain amplitude control, could not contain the stain limits and a much larger hysteresis loop resulted.

These conditions lasted for a number of cycles indicating a very large accumulation of elasticly stored energy in the crystal. After about 19 cycles the programmed constant plastic strain amplitude cycling was slowly returning. However, it was also observed that at these strain instabilities a new slipline appeared on the surface of the specimen. With the energy parameter approach these changes can be numerically analysed. Calculating β_E for cycle No 16401, of the order of 0.7, the drop is of the order of 10% on the previous cycle.. Each subsequent cycle produced a higher and higher β_E and cycle No 16420 was operating with a β_E value very close to that of cycle No 16400, of the order of 0.8. The explanation may be as follows: the new sliplines operate with large frictional resistance initially and thus the average frictional stresses rise. As further cycling takes place these slip systems harden and the energy parameter increases. This increase in elastic interaction prepares the specimen for further yielding, new slip planes start to operate, and the process repeats itself. General cyclic hardening in these alloys therefore is different from those alloys with higher s.f.e. and under the experimental conditions hardening takes place till the specimen fractures in fatigue. There is no plateau developing similarly to those with Cu or Cu with low Al content.

Similar strain burst are observed in crystals with higher aluminium content as shown in Fig 15. With the 7 at % Al crystals this strain instability is observed only at low plastic strain amplitude cycling while with 11 and 16 at % Al content the instability was observed with all the used strain amplitudes.

CONCLUSIONS

The results indicate that the plastic instability exhibited by the investigated structural steel and a number of Cu-Au alloy single crystals cannot be explained with reference to stress and strain only. The actual hysteresis behaviour becomes a useful index and with the Bauschinger energy parameter a numerical approach can be taken towards the deformation processes involved in any stage of the cyclic state. Accordingly, plastic instability takes place when the energy parameter increases, that is when the dislocation-dislocation interaction or dislocation to obstacle interaction raises the elasticly stored energy to the extent that the deformed state is ready to expand into the undeformed volume of the specimen. This is in a form of Luders type expansion in the case of the structural steel and new slip plane formations in the case of the Cu-Al single crystals.

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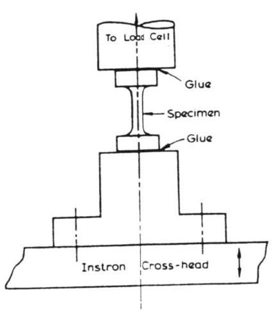
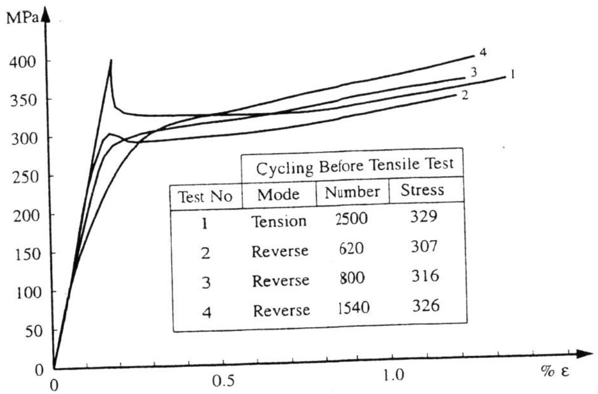
Fig. 1



Testing arrangement.



Test No	Cycling Before Tensile Test: Mode	Number	Stress
1	Tension	2500	329
2	Reverse	620	307
3	Reverse	800	316
4	Reverse	1540	326

FIG.2. TENSILE RESPONSE AFTER CYCLING.

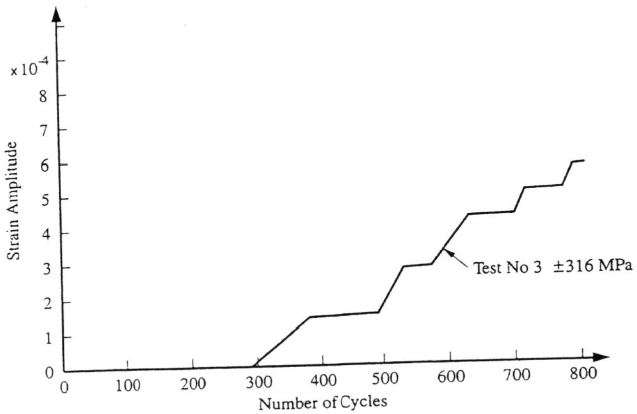


FIG.3. SOFTENING TREND DUE TO CYCLING.

FIG.4. POLISHED SINGLE CRYSTAL SPECIMEN

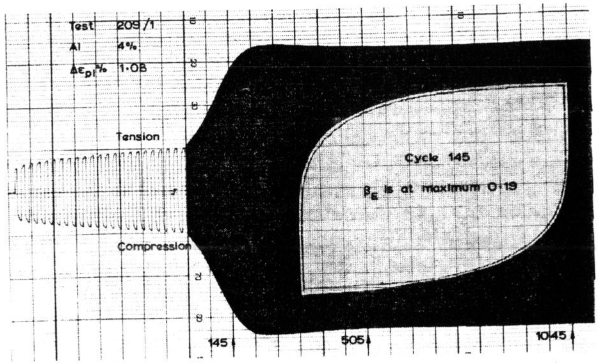


FIG.5. CYCLIC HARDENING RESPONSE OF CU-4 AL SINGLE CRYSTAL

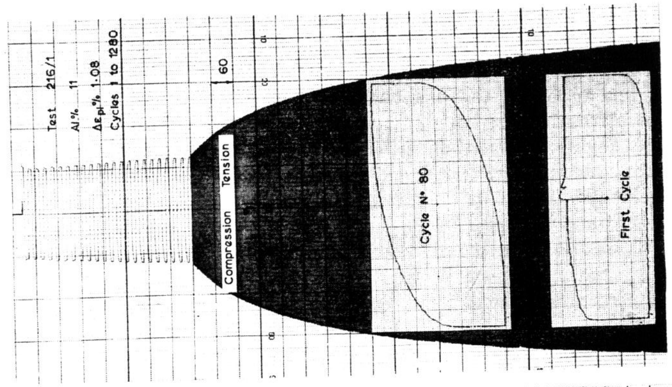


FIG.6. CYCLIC HARDENING RESPONSE OF CU - 11 ALL SINGLE CRYSTAL

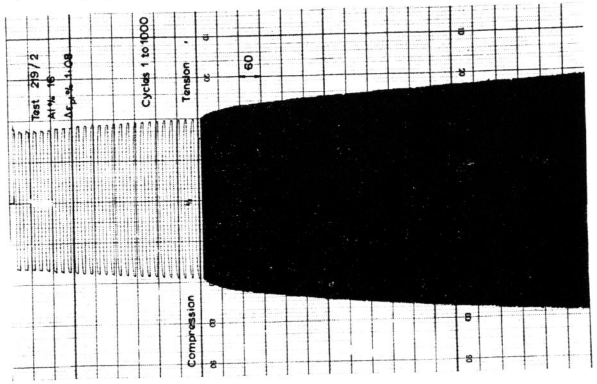


FIG.7. CYCLIC HARDENING RESPONSE OF CU - 16 AL SINGLE CRYSTAL

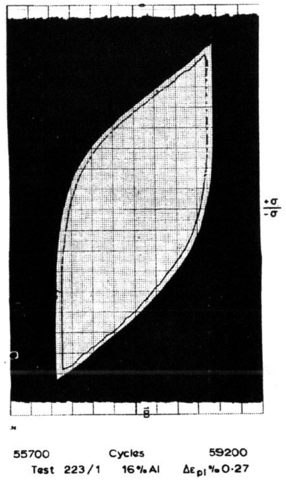


FIG.8. HYSTERESIS LOOP SHAPE OF CU-16 AL ALLOY AT LARGE NUMBER OF CYCLES

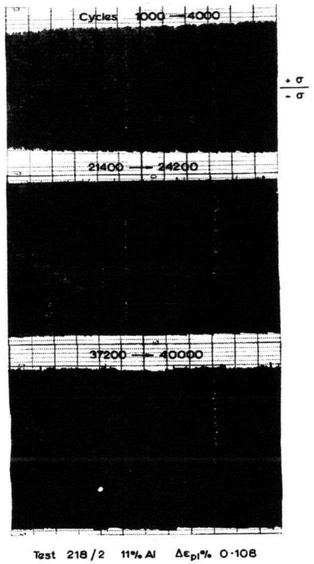


FIG.9. PEAK STRESS IRREGULARITIES AT VARIOUS CYCLING STAGES

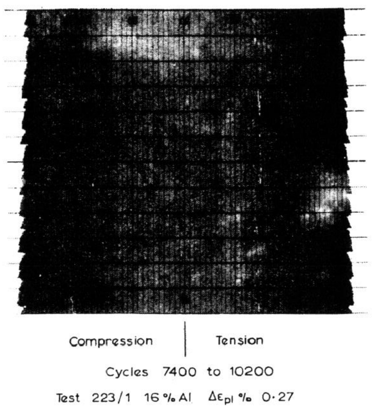


FIG.10. PEAK STRESS IRREGULARITIES OF CU-16 AL ALLOY.

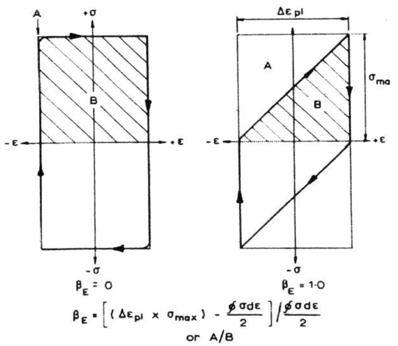


FIG.11. THE DEFINITION OF THE BAUSCHINGER ENERGY PARAMETER, β_E.

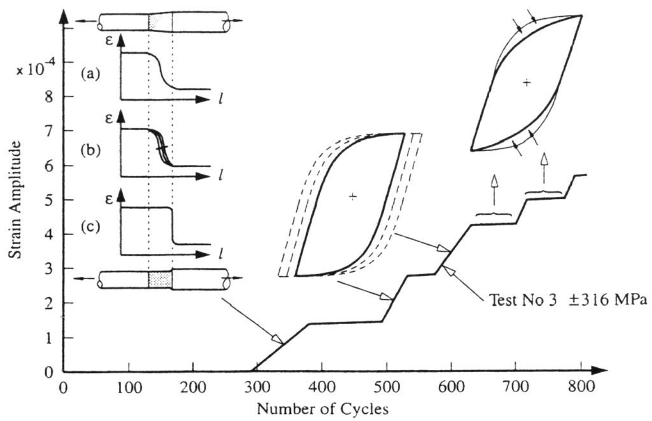


FIG.12. SOFTENING MODE IN STRUCTURAL STEEL.

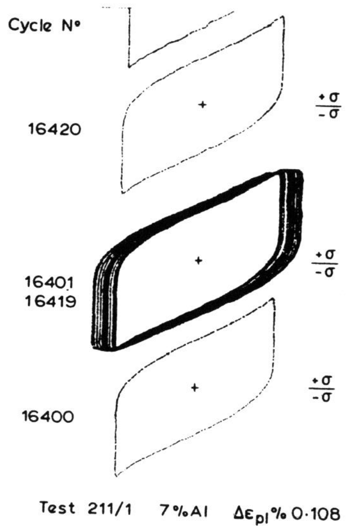


FIG.13. HYSTERESIS BEHAVIOUR AT PLASTIC INSTABILITY.

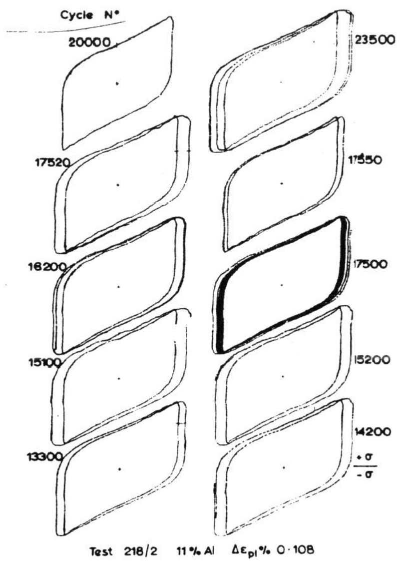


FIG.14. PLASTIC INSTABILITY
WITH CU - 11 AL ALLOY

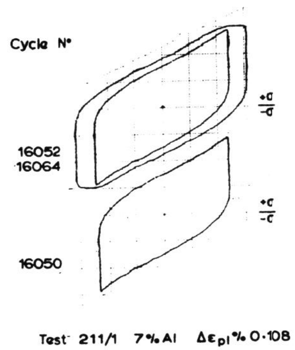


FIG.15. HYSTERESIS BEHAVIOUR
AT PLASTIC INSTABILITY