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A comparison of uniaxial and rotating bending fatigue tests on an acetal co-polymer

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Using the same type of injection moulded specimen, uniaxial and rotating bending fatigue tests have been carried out and the results compared. In each type of testing conventional fatigue or thermal softening failures occurred depending on the loading conditions. Much higher cyclic frequencies could be used in rotating bending without causing thermal softening failure. Injection moulding produces a skin at the surface of the specimens which is more resistant to fatigue crack initiation than the internal structure. Since the maximum stress in bending is at the surface, the skin effect contributes to the much larger fatigue endurances observed in rotating bending. A sharp V-notch, a diametral hole or a moulded weld line in the specimens reduced endurances in both types of fatigue loading to various extents.

1. Introduction

The most common types of fatigue test utilize flexural bending, rotating bending or uniaxial push-pull and there are advantages and disadvantages in each system. Uniaxial testing machines are usually bulky and expensive which means that a bank of the more compact and relatively inexpensive bending rigs could be set up at a cost similar to that of one uniaxial rig. In bending, however, there is a stress gradient across the specimen which for a viscoelastic material is more complex and this must be compared with the uniform stress in a specimen under uniaxial cyclic load. Bending tests may appeal more to industry, so that fatigue data may be accumulated for a variety of materials on a bank of machines. However, from the research point of view, the advantages of having a uniform stress across the specimen test section often outweighs any disadvantages of size or additional cost of the machine. For this reason the polymer fatigue studies carried out in this research programme were initiated using a servo-controlled uniaxial fatigue machine and the results have been reported [1-3]. However, the importance of using a bending mode of fatigue testing was recognized and so the fatigue studies have been expanded to include rotating bending fatigue. A bank of three machines was set up and by using the same specimen as for the uniaxial work the results could be compared directly with the results in uniaxial fatigue.

Several papers have been published on the bending fatigue of polymers and the majority of these tended to favour plane bending. Gotham [4], Kurobe and Wakashima [5] and Hutchinson and Benham [6] all utilized this type of testing to examine the conventional type of fatigue failure. Riddell *et al.* [7] and Constable *et al.* [8] used it to examine the thermal aspect of failure although the latter authors also did some tests using rotating bending.

2. Specimens and apparatus

2.1. Material

It was considered to be more useful in a study of the basic parameters of polymer fatigue initially to do a comprehensive investigation on one material rather than a less detailed study on a range of polymers. After consultation with the plastics industry, an acetal co-polymer was selected as a suitable material. The specimen shape takes the form of a hollow cylinder, 20 mm o.d. and 10 mm i.d., with conical end sections for gripping [1-3]. This shape has the advantage that it is suitable for both uniaxial and rotating bending fatigue thereby avoiding problems such as size effects and material condition.

Finally, since components made from thermoplastic materials are invariably moulded it was decided to injection mould, rather than machine, the specimens. The standard plain test specimen was produced by injecting the polymer into the mould through a gate at one end of the specimen but the mould was specially designed so that specimens could also be produced by using (a) a side gate at the middle of the parallel section, or (b) gates at each end of the specimen. This meant that moulding defects such as sprue marks and welds could be deliberately introduced and their effects on fatigue examined.

2.2. Apparatus

The uniaxial fatigue machine has been described in detail elsewhere [3]. The rotating bending fatigue machines were modified versions of fatigue machines used for metals. The principle of operation may be seen in Fig. 1. A pure bending moment, M, is applied by deadweight to the specimen which is supported at one end in a bearing block and is rotated by an electric motor. The number of revolutions is recorded on the counter and when the specimen fails the pulley wheel turns clockwise which operates a microswitch and causes the motor and cycle counter to stop. The frequency of cycling on one machine can be varied from 2.5 to 25 Hz while the other two machines have a fixed speed of 50 Hz. An infra-red radiation thermometer was used to detect any temperature rises which occurred on the surface of the specimens during cycling.

3. Results and discussion

As was shown in the earlier work, when acetal is subjected to a cyclic stress, failure can occur by one of two quite separate phenomena. The high damping and low thermal conductivity of the material means that when a cyclic stress is applied the temperature of the specimen increases. This can take one of two forms depending on the combination of cyclic frequency, stress level and specimen geometry. During load controlled cycling and for any selected frequency and specimen shape, a low applied cyclic stress causes the temperature of the material to rise but after a period this increase steadies off and the temperature of the material remains at the new level until eventually, if the applied stress is above the endurance limit, failure occurs by a conventional brittle type of fatigue fracture. As the value of applied cyclic stress is increased higher stable temperature rises can occur until eventually a stress level is reached where the temperature rise no longer stabilizes. Instead there is a continuous increase

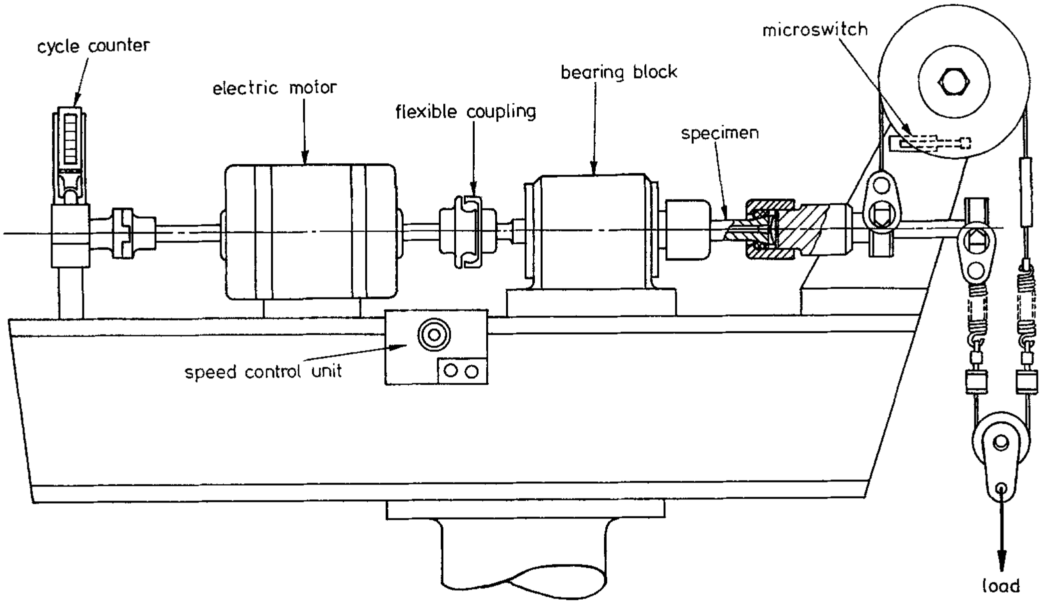

Figure 1 Rotating bending fatigue machine.

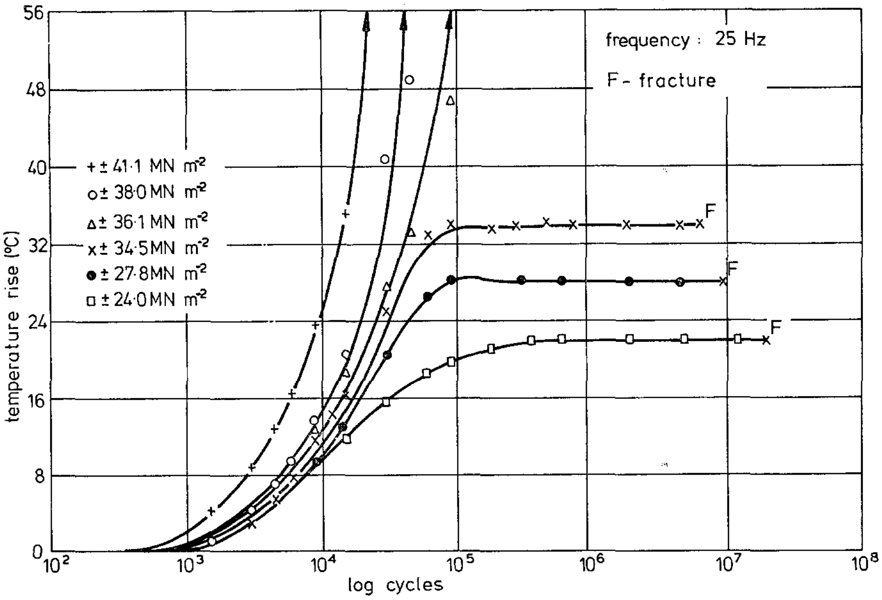

Figure 2 Temperature rise during rotating bending fatigue testing of acetal.

in temperature causing failure of the material through a drastic drop in modulus. The maximum stable temperature rise in uniaxial cyclic stressing of acetal was found to be approximately 20° C. The value of stress to cause this maximum at any frequency was found to depend on the cyclic waveform and whether the loading cycle was repeated tension or fully reversed. However, when comparing uniaxial fatigue behaviour with that in rotating bending, uniaxial tests in which the load was controlled under a fully reversed sinusoidal waveform are used as the basis for comparison.

The first thing to note about the rotating bending tests on acetal is that, as in the uniaxial tests, the temperature of the material rises and then either stabilizes to result in a brittle fatigue failure or continues to increase and causes a thermal softening failure. Figs. 2 and 3 illustrate the typical characteristics at 25 and 50 Hz. These have a similar shape to the temperature rise curves described elsewhere [1-3] for uniaxial fatigue testing but the magnitudes of temperature rises and applied stresses are different. For example, in rotating bending the maximum stable temperature rise is approximately 40° C as compared with 20° C in uniaxial loading. This is probably to be expected when it is remembered that only the outer surface is at the maximum stress in rotating bending and so heat transfer can occur into the lower stressed inner material as well as out from the surface.

In addition to the higher surface temperatures attainable in rotating bending higher stresses can also be used at any frequency before thermal failures occur. For example, at 5 Hz in uniaxial cycling thermal failures occur for stresses above $\pm$ 21.6 MN m^{-2} and clearly if the frequency was increased it would be necessary to reduce this stress in order to avoid thermal failures. However, in rotating bending the frequency can be increased five fold (25 Hz) and this stress can still be used with a relatively small temperature rise. In fact at 25 Hz in rotating bending thermal failures only occur for stresses above $\pm$ 35 MN m^{-2} which corresponds with a measured surface strain of $\pm$ 0.94%*.

This latter fact would obviously be a great advantage if the fatigue curves in rotating bending and uniaxial fatigue were similar because the higher frequencies would mean much shorter testing times. Unfortunately, as shown in Fig. 4, this is not the case because fatigue endurances are very much longer in rotating bending. In uniaxial loading the whole cross-section is subjected to the maximum stress

*A Huggenberger extensometer was used to measure the surface bending strain on the specimen mounted in the machine under various static bending moments. A virtually linear bending stress-bending strain relationship was obtained up to 35 MN m^{-2} having a slope (flexural modulus) of 3.73 GN m^{-2}.

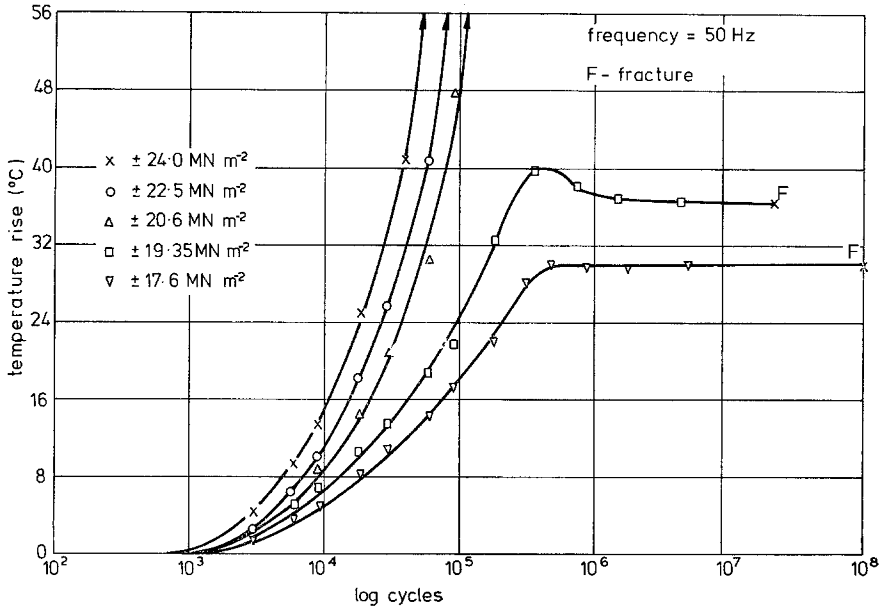

Figure 3 Temperature rise during rotating bending fatigue testing of acetal.

whereas in rotating bending it is only at the outer surface. Therefore, since fatigue failure depends on cracks being initiated the greater area under maximum stress in uniaxial loading increases the probability of a suitable crack initiation site in that mode of testing. In addition there is the problem with moulded specimens that the cross-section of the specimen is not homogeneous due to formation of a tough skin at the mould surface. It was noticeable from examination of uniaxial fatigue fractures that, with the opportunity to select any initiation site through the specimen cross-section, failure usually initiated from within the wall thickness indicating greater weakness in that area than at the surface. In rotating bending the maximum stress acts on the tougher skin or at least on the region which, as was shown in the uniaxial tests, is less

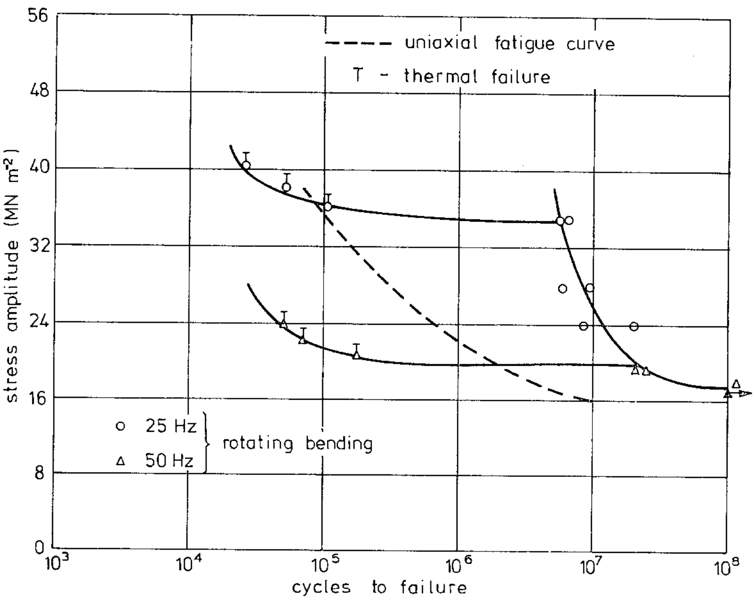

Figure 4 Comparison of rotating bending and uniaxial fatigue behaviour of acetal.

likely to favour crack initiation. As a final point there is the fact that in uniaxial testing any crack, once it has initiated, propagates into a region under the same nominal stress whereas in rotating bending the crack is tending to propagate into an area under the lower nominal stress. It is difficult to analyse the exact nature of the differences in crack growth behaviour because in rotating bending there is the additional problem that as the crack grows the specimen geometry, on which the stress is calculated, effectively varies.

Fig. 4 shows that the endurances in the two modes of fatigue differ by a factor approaching 100 at stress levels of about $\pm$ 40 MN m^{-2} but this reduces to around 10 at stresses in the region of $\pm$ 16 MN m^{-2}. As in uniaxial loading, the temperature rise in acetal during cyclic loading does not have any marked effect on the endurance. The data at 25 and 50 Hz coincide fairly well and the scatter is no more than would be expected in fatigue results.

3.1. Effect of notches

In order to compare the effects of intentional stress raisers on each method of fatigue testing a 1 mm deep circumferential V-notch with a tip radius of 0.05 mm was carefully machined into a number of specimens. This produced an elastic stress concentration factor of 8 as shown by Peterson [9]. In uniaxial loading the notch did not produce as large a reduction in endurance as might have been expected from the stress concentration factor. The effect of the notch was more marked in rotating bending with quite a considerable reduction in fatigue life particularly at the higher stresses. This could most probably be explained by the fact that the tough moulded skin has been penetrated at least partly by the notch thus accelerating the crack initiating process at the surface. However, it must be remembered that the plain specimens as they are referred to in Fig. 5 are only plain in the sense that they do not contain any intentionally introduced stress raisers. As pointed out earlier, they are not plain in the true sense of the word because they do contain preferential crack initiation and/or propagation areas within the wall thickness in the form of microscopic voids. With this in mind it is reasonable to assume that if these inherent flaws or defects could be removed the plain uniaxial fatigue curve would be moved to the right although by how much remains a matter for speculation. The point that is clear from the foregoing remarks is that the notch results probably give a better comparison between uniaxial and rotating bending fatigue because in these tests initiation and propagation

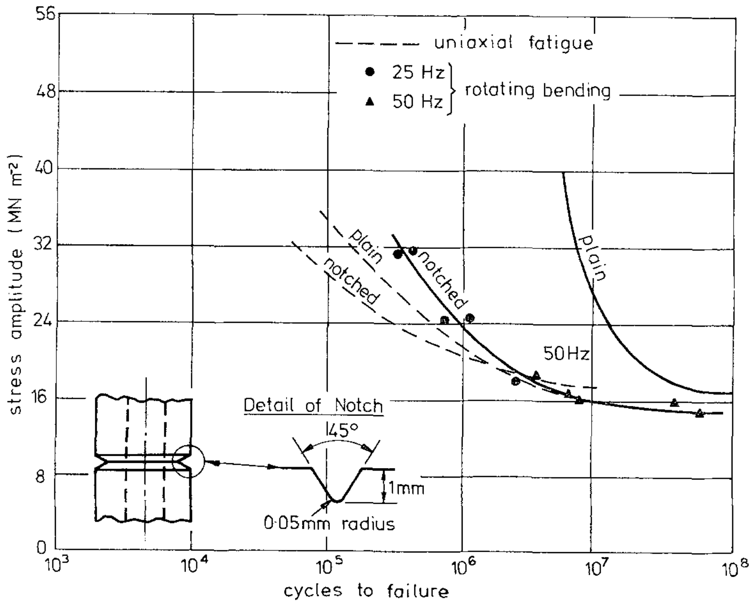

Figure 5 Comparison of the effect of a sharp V-notch on uniaxial and rotating bending fatigue.

has occurred from the same region – the root of the notch in each case.

3.2. Effect of a hole

In the uniaxial work described elsewhere [1-3] a 2.5 mm diameter hole across the diameter of the specimens was used as an alternative form of stress raiser. In these tests it was found that the hole caused a more detrimental effect to fatigue endurance than the V-notch even though the elastic stress concentration factor was only 2.6 as compared with 8 for the V-notch. Similar tests were, therefore, performed in rotating bending and the effects can be compared in Fig. 6. In rotating bending fatigue the specimens with a transverse hole had slightly longer fatigue endurances than those with a V-notch, thus reversing the effect observed in uniaxial loading. The explanation for this is once again tied up with the fact that there is a region within the wall thickness of the specimens which appears to be a more favourable area for crack initiation. In uniaxial loading since the hole passes right through the specimen cracks can initiate in the most favourable region and examination of the fracture surfaces showed this to be the case. In rotating bending the maximum stress was only at the surface and it is necessary for cracks to initiate around the hole in the tougher skin area.

3.3. Effect of a weld

As a final basis for comparison the effects of a moulded defect was examined. In an earlier section it was pointed out that special moulds had been designed for the specimens so that typical moulding defects could be produced as required. For example, a weld defect was introduced into the centre section of the specimens by having polymer injected through gates at each end. In these tests it was also considered important to examine at least qualitatively the effect of moulding conditions and so the weld was produced using good moulding conditions (A) and also using a variation from these in terms of a different set of moulding parameters to produce a relatively poor moulding (B). In uniaxial fatigue both moulding conditions A and B were found to have poor fatigue strengths. Condition B, as would be expected, was the worst of the two but both conditions resulted in fatigue endurances considerably less than the V-notch or even the transverse hole. Fig. 7 shows the effects in rotating bending and it can be seen that in comparison to the reductions observed in uniaxial fatigue the weld does not result in such a detrimental effect. In fact, in condition A there does not appear to be any reduction in fatigue strength. As before, the explanation probably lies in the necessity of initiating cracks at the

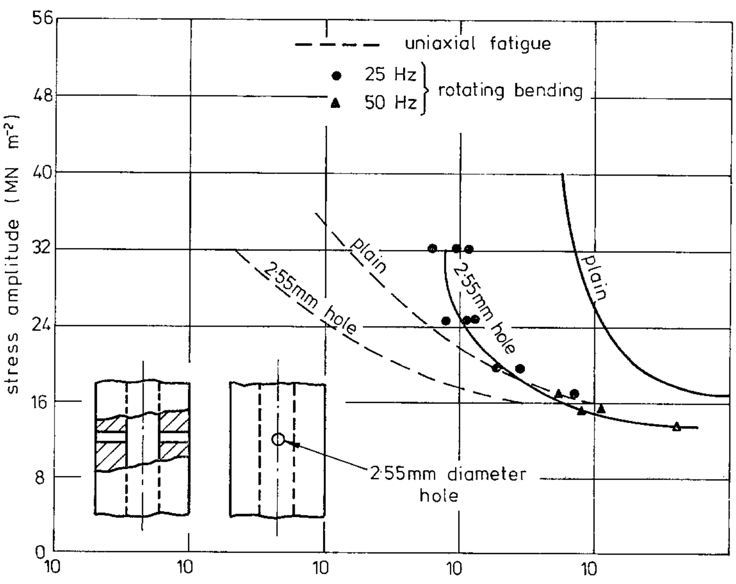

Figure 6 Comparison of effects of transverse hole on uniaxial and rotating bending fatigue.

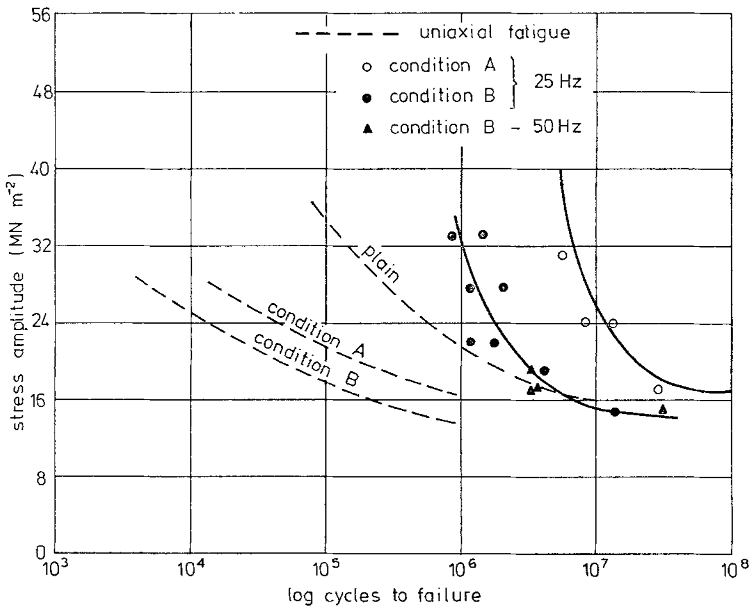

Figure 7 Comparison of the effect of weld defect on uniaxial and rotating bending fatigue.

outer surface in rotating bending where the detrimental effect of the weld line is compensated by the tough skin.

The stress gradient across the specimen in rotating bending has, therefore, improved the fatigue endurances of the specimen in the majority of the tests by having to initiate cracks from the tough surface and by only exposing the weaker inner material to lower stresses. However, although the slopes of the fatigue curves in rotating bending are fairly steep at the higher stresses it is possible to envisage a situation where, as the surface stress is increased, the stress gradient is sufficient to produce an internal stress level which could initiate and propagate cracks from the weaker region within the material. This would then cause a change in the fatigue curve to a less steep region at the higher stresses due to fatigue cracks propagating from within the material and not from the surface.

4. Conclusions

1. When acetal is subjected to rotating bending fatigue the temperature of the material rises and either stabilizes at some value until a conventional type of fatigue fracture occurs or the temperature continues to increase and causes a thermal softening failure in the material.

2. It is possible to obtain a higher stable temperature rise in rotating bending than in uniaxial loading for the same nominal stress.

3. It is possible to use much higher cyclic frequencies in rotating bending as compared with uniaxial fatigue without causing thermal softening failures.

4. Endurances are considerably greater in rotating bending fatigue compared with uniaxial fatigue for the same surface stress.

5. There is a skin effect on moulded specimens which is less sensitive to fatigue crack initiation than the bulk of the material.

6. In general the effect of a machined V-notch and transverse hole on rotating bending fatigue is to reduce endurance. However, it is difficult to compare the fatigue life reduction factors with those in uniaxial fatigue testing because of the skin effect.

7. A weld line produced during moulding is extremely detrimental to uniaxial fatigue and can also reduce fatigue endurances in rotating bending for moulding conditions less than optimum.

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