CREEP RUPTURE FAILURE UNDER CONDITIONS OF STATIC STRAIN

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Abstract

The response of polymeric materials under long-term loading will vary due to several interrelated factors including time, temperature, and the magnitude of loading experienced by the material. A common failure mode encountered in plastic parts under long-term loading is creep rupture. Creep rupture describes a slow-crack growth failure in polymeric parts that is a consequence of molecular disentanglement over time as a result of exposure to continuous stress. This time-related phenomenon can lead to unexpected failures in plastic parts after days, months, or years in service. While creep rupture is more predictable and better understood under constant stress loading, creep rupture resulting from a constant strain condition is frequently encountered in several applications and is more complex to interpret. This complexity is due to the competing mechanisms of plastic creep and stress relaxation. This paper will provide insight into several long-term material behaviors in polymeric materials, with an emphasis on a scenario involving creep rupture as a result of constant strain over time.

Background

The viscoelastic nature of polymeric materials, inherent because of their macro molecular structure, leads to temperature dependence. In general, the temperature dependence of plastics has been well documented and is commonly understood. However, viscoelasticity also produces time dependency within plastics, and this is often overlooked. Because of their polymeric nature, the properties of plastics are subject to change based upon time and loading history.

Just as physical properties determined at ambient temperature cannot predict the performance at elevated temperature, short term properties cannot project the long term performance of plastics. Understanding the time dependency of plastic part performance is important to avoid premature and unexpected failure. The performance of the molded plastic part, the tangible manifestation of the design and processing, is limited by the physical, mechanical, and thermal properties of the material. Failure to understand these properties can lead to catastrophic consequences. Failure associated with the exertion of stress over time accounts for a significant number of failures within plastic components. One study attributes 22% of all plastic component failures to such mechanisms[1].

Creep

Creep is the time-dependent change in the dimension of a plastic article when it is subjected to a constant stress[2]. The stress can be applied through tensile, compressive, shear, torsional, or flexural loading. Regardless of the form, normal stress (σ) is the ratio of the applied force (F) divided by the cross-sectional area of the loaded member (A), as follows:

$$\sigma = \frac{F}{A}$$

As indicated above, creep is important in plastics because of viscoelasticity. Common design features that expose a plastic material to static stress include structural components such as beams, columns, and hanging supports; reinforcing bars with torsional loading; and pipes and tanks under hydrostatic pressure.

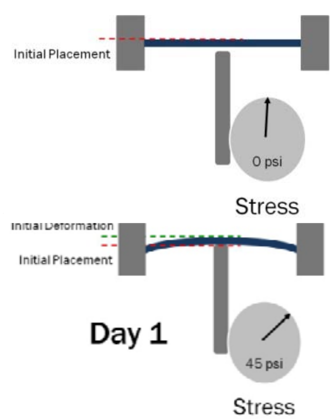
Creep can also be observed within metals, but predominantly at elevated temperatures. In most cases, the creep behavior of metals is insignificant at ambient conditions.

Within plastics, the exertion of static stress loading results in dimensional changes within the component over time, as shown visually in Figure 1. In this illustration, a plastic specimen is subjected to tensile loading through bending. Over time, given a constant load on the plastic specimen, a change in length is observed. This change in length is known as strain (ε) and is the ratio of stress (σ) divided by the modulus of the material (E), as follows:

$$\varepsilon = \frac{\sigma}{E}$$

Modulus is a fundamental physical property of the material, and essentially represents the stiffness. The modulus of a plastic material is both temperature and time dependent. Over time at a static stress, the apparent modulus of the plastic material will gradually decline.

Failure within a plastic article through creep loading can occur either through excessive deformation that renders the part dimensionally unusable or through cracking associated with creep rupture.



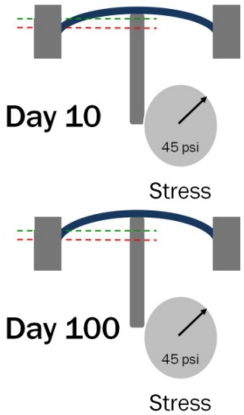


Figure 1: Graphical representation of the change in dimension over time associated with creep from the application of static stress.

Stress Relaxation

Stress relaxation is the time-dependant reduction in stress within a plastic article when it is subjected to a constant strain[3]. Essentially, stress relaxation describes the polymer's propensity to shift its molecular arrangement to achieve a lower stress state[4]. This is illustrated in Figure 2, where a sample is placed under a bending load and the strain is held constant. Over time, while under static strain, the measured stress required to maintain a constant deflection or deformation in the specimen will decrease.

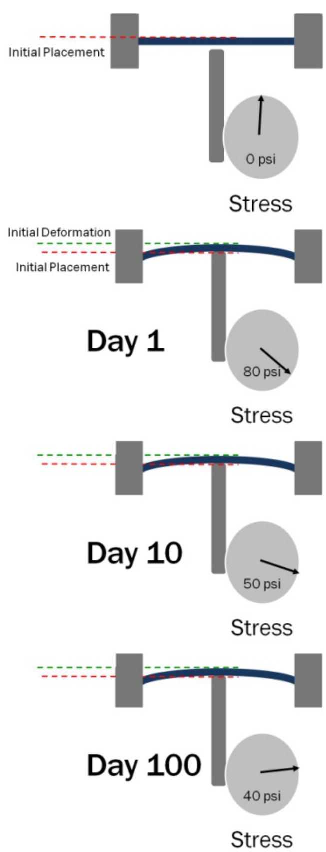


Figure 2: Graphical representation of the change in stress over time associated with stress relaxation from the application of static strain.

Stress relaxation differs from creep in the fact that the viscoelastic properties inherent to plastics result in a reduction of stress while under constant strain, whereas creep refers to a change in the strain while under a constant stress. Although creep and stress relaxation lead to different measureable properties within the plastic due to the differing loading conditions, the molecular rearrangement mechanism is relatively similar in both cases. With both mechanisms a reduction in apparent modulus is observed over time. In stress relaxation, this reduction in apparent modulus occurs at a constant strain, as represented in Figure 3[5] from dynamic mechanical analysis - time temperature superposition experimentation.

The stress relaxation properties of a material can be defined by determination of the relaxation modulus ($E_r(t)$), a time dependant elastic modulus for viscoelastic polymers. This time-dependant property is determined by measuring the stress response in a material over time ($\sigma(t)$) while under constant strain (ε_0), as follows[6]:

$$E_r(t) = \frac{\sigma(t)}{\varepsilon_0}$$

The non-linear relaxation modulus is proportional to the stress present in the material over time while under a constant strain. In order to obtain a detailed understanding of the stress relaxation for a given plastic material, isothermal measurements of the relaxation modulus must be collected over the intended temperature range of use, as the relaxation modulus is also temperature dependant. In general, the magnitude of the relaxation modulus will decrease as the temperature increases.

Stress relaxation is an important property of plastics that can be both advantageous and detrimental to their performance. The stress relaxation mechanism can be beneficial as it is responsible for the relief of residual and assembly stresses in plastic articles. One example where this is advantageous is the annealing process commonly used in plastic product manufacture, where increasing temperature can accelerate reduction of stress in a plastic article.

However, stress relaxation can be unfavorable and lead to performance failure if the application requirements dictate that a certain stress level be maintained within the material, such as interference fits and sealing applications. This is illustrated in Figure 4[7] derived from the data presented in Figure 3 using a constant strain of 4%. Stress relaxation is important in a wide range of plastic design features including bosses with inserts, members under fixed radius bending loads, snap fits, and fasteners. Within plastic components and assemblies, static strain-based designs that lead to stress relaxation are more prevalent compared with static stress-based designs that are associated with creep.

It is important to consider the level and rate of stress relaxation that can occur within a given plastic material. When the stress levels in the material exceeds the level at which they can be adequately relieved via stress relaxation, molecular disentanglement can occur resulting in crack development via creep rupture.

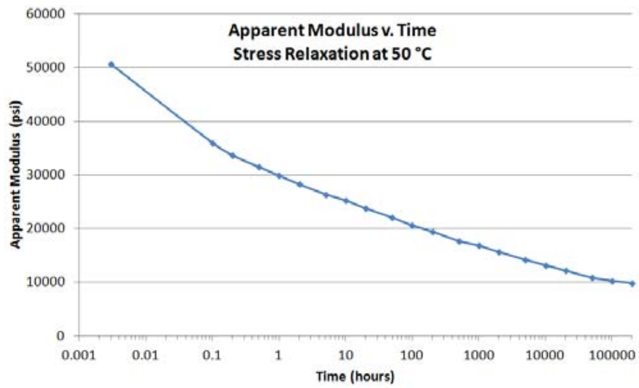


Figure 3: Graphical representation of the reduction in apparent modulus for a polypropylene resin under conditions of stress relaxation.

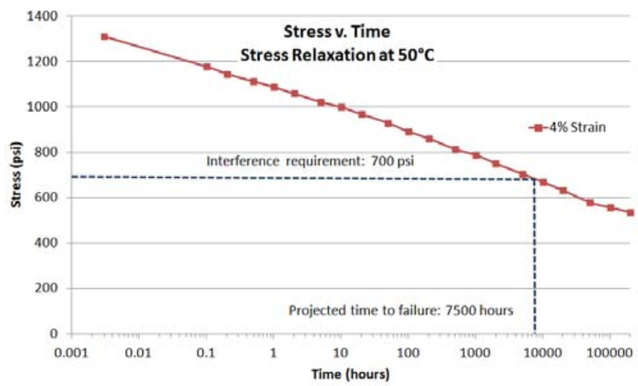


Figure 4: The reduction in stress resulting from the decline in apparent modulus for a polypropylene resin is shown. The failure time is projected when the stress drops below the minimum allowable interference stress.

Creep Rupture

Creep rupture is the formation of cracks that occur as a function of time associated with exposure of a material to continuous stress, below the yield strength of the material. This stress can be constant as in a static stress condition, or diminishing but continual as in a static strain condition. Both of these scenarios result in decay of the apparent modulus through localized molecular reorganization of the polymer chains.

Because the stress level is below the yield point of the material, molecular reorganization takes place exclusively through disentanglement, as there is no opportunity for yielding. The exertion of low to moderate stress over an extended time leads to apparently lower ductility within the plastic. Thus, such slow disentanglement generally results in brittle fracture in normally ductile plastic materials.

While it might seem complex, it is important to remember that cracking is simply a response to stress. Fracture takes place as a stress relief mechanism. Ductile fracture is a bulk molecular response that occurs through yielding, a macro molecular rearrangement, followed by disentanglement. Conversely, brittle fracture is a micro molecular response where disentanglement is favored over yielding.

In the case of a static stress condition, the level of stress acting on the component is continuous and constant. In this situation, prediction of the time to failure can be performed through time-temperature superposition via dynamic mechanical analysis[8]. In general, the lower the level of applied stress, the longer the time to creep rupture. In addition to requiring more time, lower levels of applied stress result in brittle fracture, whereas higher levels of stress can produce ductile failure. This is illustrated in Figure 5[9].

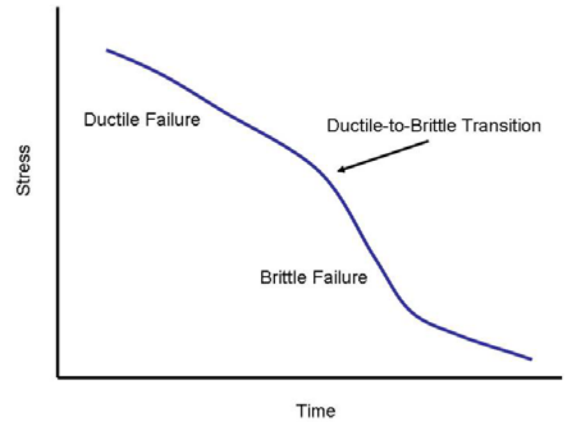


Figure 5: A representative creep rupture curve showing the relationship between applied stress and the time to creep rupture.

Long-term creep fracture can be represented by statistical distributions of the applied stresses and the part strength[10,11]. As previously discussed, plastic creep will result in a reduction of apparent part strength over time when continuously stressed. In a constant stress scenario, as represented in Figure 6, the apparent part strength distribution will reductively shift towards the applied stress distribution over time due to creep. This results in an increased probability of failure via creep rupture when the two distributions overlap.

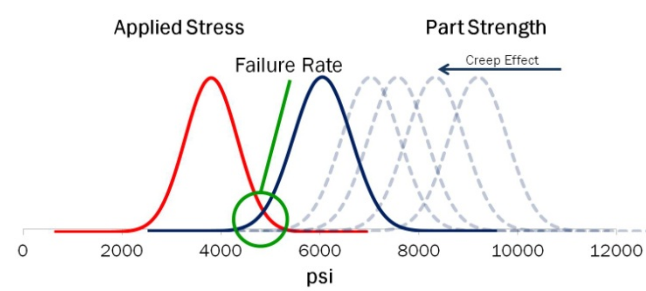


Figure 6: Graphical representation of the apparent reduction in strength over time associated with creep in a constant stress condition.

In cases involving static strain, the concept and the failure prediction are not as straightforward. In static strain situations there are two competing mechanisms, the disentanglement associated with creep and the progressive reduction in the stress loading from stress relaxation. A constant strain scenario will also produce a reduction in the apparent part strength. Additionally, however, stress relaxation will lead to a reduction in the applied stress distribution, as presented in Figure 7. This shifting of both distributions will result in an altered failure rate, as well as extension of the time to failure since it will take longer for the two distributions to overlap. This link between stress relaxation effects and part strength reduction via creep is important when considering creep rupture in a constant strain scenario.

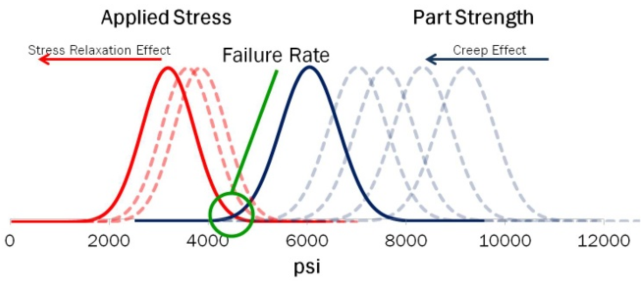


Figure 7: Graphical representation of the apparent reduction in strength over time associated with creep and the reduction in applied stress over time associated with stress relaxation in a constant strain condition.

The competing creep and stress relaxation mechanisms associated with a constant strain condition combine in a way that complicates the prediction of failure mode, either relaxation or rupture, as well as the time to failure. Because the stress is constantly diminishing, the effects on the part are also being reduced from the initial state. The dominant factor, creep or stress relaxation, is dependent on the initial stress / strain condition, the material, and the environmental conditions. Under conditions of constant strain, stress relaxation will continue, but eventually the relaxation effect will essentially equilibrate, resulting in effectively a constant stress condition.

A generalized conceptual graph illustrating the projected relative time to failure and the failure mode under conditions of constant strain is proposed, as presented in Figure 8. This is not meant to be a design guide, but instead serves to exemplify the combination of interference strain and load.

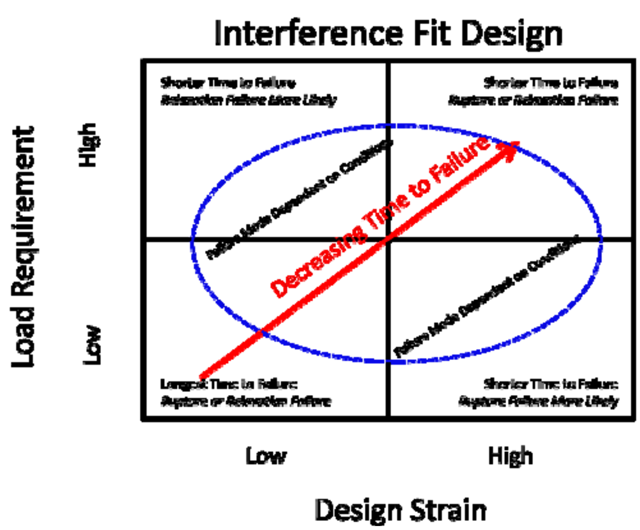


Figure 8: Conceptual representation of the responses that can occur under conditions of various static strain levels in conjunction with extremes of interference load requirement.

For example, if a part with molded-in metal inserts has a high initial interference strain and a low interference load requirement, it is anticipated that creep rupture will occur due to the interference stress within the plastic bosses after a relatively short period of time. Conversely under conditions with a low interference strain and a high load requirement, it is expected that the failure mode will be relaxation with a loss of the insert from the boss.

It is important to note that the creep rupture mechanism can be accelerated by numerous factors including

- exposure of the plastic to chemicals agents
- thermal events
- the application of dynamic stress loading
- stress concentrating design features
- molding defects, such as voids and inclusions
- knit lines

All of these factors can diminish the intermolecular forces bonding the polymer chains and facilitate premature failure

Case Illustration

Injection molded caps were evaluated as the parts had cracked after assembly and while in storage, prior to use in service. The caps were produced from an unfilled, high-flow grade of polycarbonate resin, and subsequently press fit onto a mating metal shaft. As installed, it was indicated that there is an interference fit between the cap and the shaft. Specifically, the inner diameter of the cap was nominally 0.120 in. The mating shaft was specified with a diameter of 0.123 in. Initial evaluation indicated some non-uniformity with the cap wall thickness. In all cases the failures occurred on the wall of the cap opposite of the injection molding gate.

The visual and microscopic examination of the caps showed longitudinal cracking on the face of the part opposite the injection molding gate. The cracking, as illustrated in Figure 9, did not show signs of detectable macro-ductility, as would be evident in the form of stress whitening or permanent deformation. In contrast, the cracking exhibited features characteristic of brittle fracture. Longitudinal cracking within a cylindrical component, such as the cap, is generally associated with hoop stress within the part. Significantly the cracking within the caps corresponded to the location where the cap mates with the underlying metal shaft. The location of the crack, opposite the injection molding gate, was suggestive of an area of poor fusion resulting from the union of two flow fronts as the mold fills. Such areas can represent locally weak locations on the molded part.

Some of the parts exhibited partial cracking, and in those caps the cracks were located approximately 0.05 in. from the open end of the cap. No evidence was found on any of the cracked caps to indicate external mechanical damage or abuse.

The identified source of the hoop stress responsible for the failure was the interference between the cap and the mating shaft. This was confirmed by examination of the cracking before and after removal from the shaft. Once the cap was removed, the cracking narrowed appreciably, as shown in Figure 10. A review of the part drawings and the indicated part tolerances showed an approximate strain within the relatively thin wall cap of 2.5% for the nominal conditions and 4.2% for the maximum tolerance conditions. A review of the appropriate polycarbonate resin datasheet indicated a typical elongation at yield of 6.0%. Thus, even under the nominal conditions, the cap wall material was under a relatively high level of strain.

Scanning electron microscopic (SEM) examination of typical opened fracture surfaces showed features indicative of crack initiation adjacent to the exterior wall of the cap, as shown in Figure 11. The fracture surface within the crack origin area displayed a relatively smooth morphology separated by individual ridges representing crack unions. These features were indicative of the initiation and subsequent coalescence of multiple individual cracks, as represented in Figure 12. The features within the crack origin zone were characteristic of brittle fracture through a slow crack initiation and growth mechanism. No evidence was found to indicate substantial micro-ductility, as would be indicated by the presence of stretched fibril formation. Examination of other areas on the fracture surface showed further evidence of brittle cracking through slow crack growth. Isolated areas on the fracture surface outside of the crack origin displayed band-like features representing alternating locations of craze remnants and smooth fracture surface morphology, as shown in Figure 13. These features are often associated with environmental stress cracking (ESC), but can also be formed through the exposure to static stresses without the presence of chemical agents. A portion of the fracture surface created in the laboratory during the opening of the fracture surface was also examined. The fracture surface features were significantly different than those observed on the failure portion of the fracture surface, as illustrated in Figure 14. The lab fracture included features associated with relatively rapid crack extension, including hackle marks and river markings. Additionally, evidence of stretched fibril formation was also present associated with ductile cracking.

The entirety of the visual, microscopic, and SEM examinations indicated that the caps failed via brittle fracture through a slow crack initiation and growth mechanism. The cracking initiated along the exterior surface of the wall. Multiple individual cracks formed within the cap and subsequently coalesced to form the longitudinal fracture. The most noticeable of the cracks extended through the complete part wall, with others only partially penetrating the wall. Overall, the observed features were indicative that the cracking initiated as a result of stresses exerted on the cap that exceeded the material's long-term strength leading to creep rupture.

Throughout the SEM examination no evidence was found to indicate post-molding molecular degradation, such as chemical attack or thermal deterioration. Further, no signs of molding defects such as voids or inclusions were evident.

Analytical testing performed on the failed cap material and the corresponding molding resin showed results consistent with an unfilled polycarbonate resin. No evidence was found to indicate significant differences between the failed and reference samples. Further, no signs of contamination, degradation or anomalous behavior were apparent.

It was the conclusion of the failure analysis that the caps failed via brittle fracture through a creep rupture slow crack initiation and growth mechanism. The source of the stress was the interference between the molded caps and the mating metal shaft. The cracking initiated within an area on the cap corresponding to contact with the adapter, thought to produce both hoop stress and bending stress within the cap wall. The sum of the interference stresses, both hoop stress and bending stress, between the two components exceeded the long-term strength of the plastic cap material resulting in failure. The cap failures occurred under conditions of static strain. The cracking took place because the creep mechanism progressed faster than the stress relaxation mechanism. In this case the design called for a relatively high design interference strain and a low to moderate interference load requirement. Failure occurred after a relatively short time through creep rupture. This is in agreement with the concept shown in Figure 8.

A contributing factor in the failure is the presence of a meld line at the failure location. Such a meld line can represent an area that is not as molecularly fused as well as other locations on the part. A second identified factor was the difference in wall thickness associated with the various walls on the cap. A relatively thinner wall represents an area which can tolerate an inherently lower level of load. Additionally, a thinner wall results in the transfer of a higher level of stress associated with the interference with the adapter to the outer diameter wall of the cap.

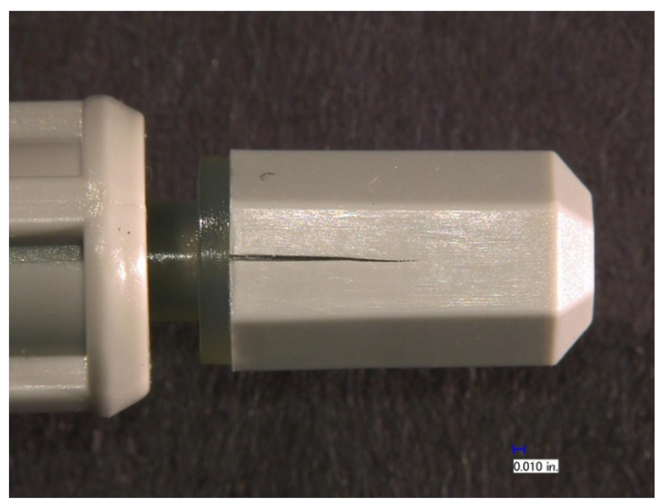


Figure 9: Photomicrograph showing cracking within a typical cap. No evidence of significant ductility is apparent.

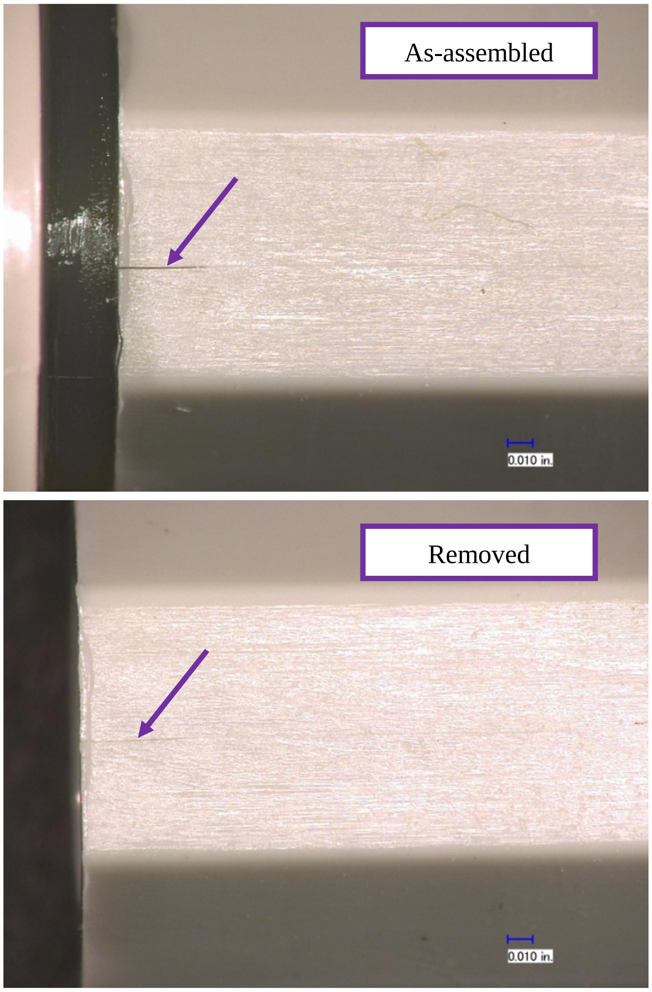


Figure 10: Photomicrographs showing the effect of removal of the cap from the shaft. Note that the crack gets appreciably narrower after removal.

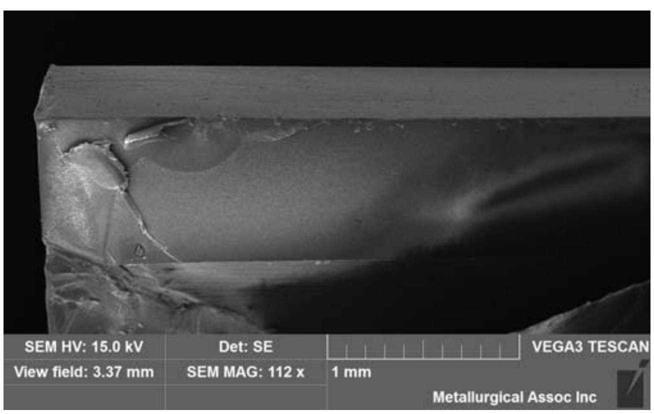


Figure 11: Scanning electron micrograph showing a typical cap fracture surface after completion. The bulk of the fracture surface exhibits a relatively smooth morphology, and presents features characteristic of brittle cracking.

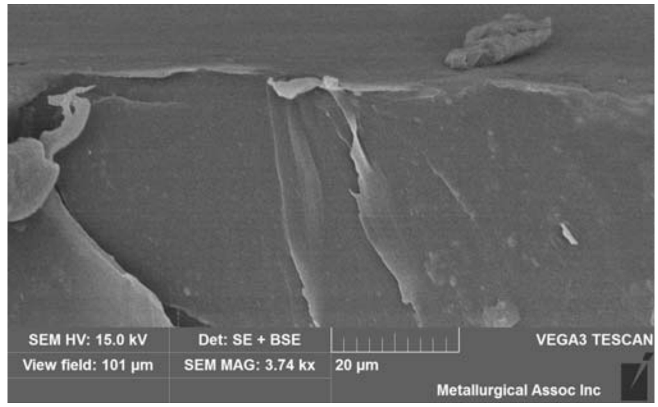


Figure 12: Higher magnification view of the upper left portion of Figure 11 showing a relatively smooth morphology within the crack initiation zone. Ridges representing crack unions are evident. Overall, the features are characteristic of a slow crack initiation and growth mechanism.

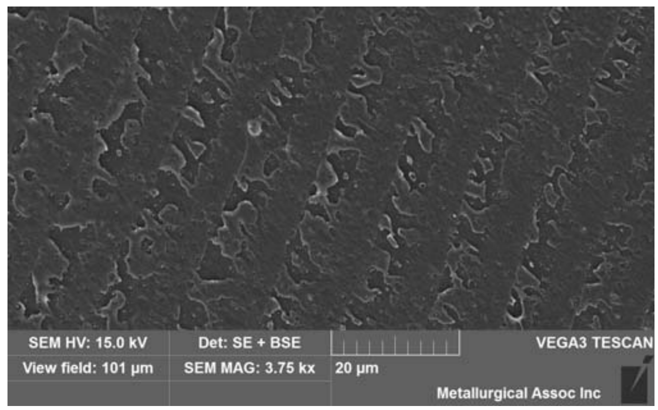


Figure 13: Higher magnification view of the central portion of Figure 11 showing an alternating band structure representing opened crazes.

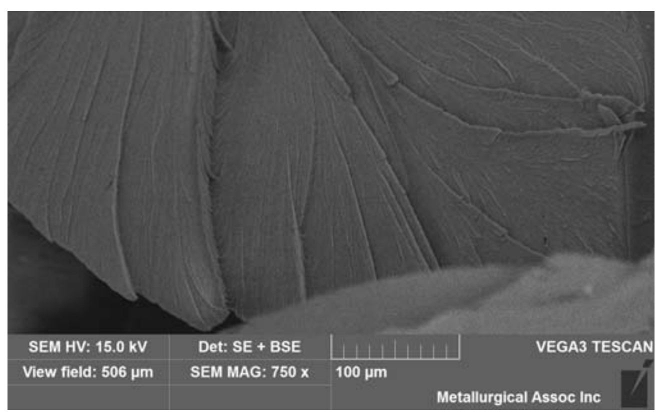


Figure 14: Scanning electron micrograph showing the features of the lab fracture zone. The features are in contrast to those of the creep rupture failure.

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Endnotes

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Keywords

Failure, Creep, Stress Relaxation, Creep Rupture