CASE STUDIES OF PLASTIC FAILURES ASSOCIATED WITH METAL FASTENERS

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Abstract

Four case studies are presented to illustrate failures associated with the interaction between plastic components and metal fasteners. The use of metal fasteners to secure and assemble plastics is widespread. The presented cases illustrate how the failure analysis process was used to identify the failure mechanism as well as the primary factors responsible for the failures. The four cases depict representative failures involving varied designs and service conditions.

Background

The need to secure plastic components is prevalent in the manufacture of assemblies in many industries, including automotive, appliances, electronics, medical, durable goods, and construction. Joining plastic components to other plastic parts or metal parts often involves the use of mechanical fasteners, such as screws, inserts, or rivets. The joining of plastic parts is inherently more complicated than assembling two metal components because of the fundamental differences in physical properties, including strength, chemical resistance and susceptibility to creep and stress relaxation.

There are a variety of fastening techniques available to the product designer. Threaded inserts are a very common way to join metal parts to plastic parts using threaded fasteners. The most common applications include the pressing of brass or steel inserts into plastic components by thermal or ultrasonic processing, or by overmolding [1]. This is achieved by melting the plastic into a knurl on the metal part, which acts as a mechanical joint once the plastic is cooled. Another widespread fastener option for plastic assemblies is self-clinching screws. Other common mechanical fastening techniques include rivets and interference springs.

One alternative to the use of metal fasteners is adhesive bonding. However, adhesive bonding has two major drawbacks. First, the exposure of the plastic material to the adhesive solvents or reactive monomers can result in environmental stress cracking within the plastic. The second disadvantage is that adhesives require time to achieve rigidity associated with set-up and curing. This requires manufacturers to wait for solidification to be completed before moving parts, which is not required with mechanical fasteners.

Another option is welding. Welding forms a bond through localized melting and resolidification of the plastic components to be joined. However, welding also has some noted disadvantages compared to the use of mechanical fasteners. A plastic welding process typical requires a relatively sophisticated technique, associated with a higher level of manufacturing skill and more costly equipment.

Another potential deleterious effect of welding is alteration of the polymer, both on microscopic and macroscopic levels. The thermal stress from welding can result in molecular degradation and crystallinity alteration within the heat-affected zone, as well as localized dimensional distortion or deformation. Welding can also produce residual stresses within the joined assembly that can drive creep rupture failure. Finally, welding can only join materials that can be melted together. For examples there are no welding processes to secure plastic and metal components.

While offering some advantages, the use of metal fasteners presents some unique problems and there are no absolute guidelines to follow when fastening plastics. Actual testing of fasteners in the plastic material is the best way to determine if satisfactory performance can be achieved. Generally, it is best to select the fastener system during the design process to effectively integrate it with other aspects of the plastic part design.

The weakest sections of many plastic part designs are the joints and assembly points[2]. Because of this, cracking of plastic components at fastener joints is common. If failure does occur within a fastened component, a failure analysis can provide a thorough understanding of the nature and cause of the failure. This knowledge is critical to correcting the failure, and avoiding future instances.

Experimental

Surfaces of the failed components were examined using a Keyence VHX-500F digital microscope and a Tescan Vega XMU scanning electron microscope (SEM). The specimens were ultrasonically cleaned in an aqueous solution of a mild detergent. Prior to the SEM inspection, the surfaces were gold sputter coated to enhance imaging.

Fourier transform infrared spectroscopy (FTIR) was performed on samples representing the materials. The analyses were conducted in the attenuated total reflectance (ATR) mode using a Thermo Scientifc Nicolet® iS5 spectrometer.

Sample materials from failed components were analyzed using differential scanning calorimetry (DSC). The testing was conducted using a TA Instruments Q5000 DSC. The analysis involved heating the samples at 10 °C/min. through the transitions of interest, control cooling the samples at the same rate, and subsequently reheating the samples. Material samples were evaluated via thermogravimetric analysis (TGA). The testing was performed on a TA Instruments Q500 TGA. The thermal program involved dynamic heating at 20 °C/min. using sequential nitrogen and air purge atmospheres.

The average molecular weights of the part materials were indirectly evaluated by melt flow rate. Tests were performed in accordance with ASTM D 1238 using an appropriate test temperature and constant load. Moisture determinations made prior to testing were conducted through Karl Fischer titration.

Tests and Results

Outdoor Enclosure – Thread Forming Screws

A relatively high number of protective panels used on an outdoor enclosure fell from the mating assembly while in service. The panels were injection molded from an unfilled, UV-stabilized, low viscosity, grade of polycarbonate. The individual panels were then secured to the plastic base using thread-forming carbon steel screws. The screws were inserted into cylindrical molded bosses on the panel. The screws were purchased from a distributor, and it was known that they were supplied by different manufacturers. The bosses were designed for a single lead 45° screw, but at the time of the assembly of the failed units, larger twin lead 48° screws were being utilized, resulting in an increased level of interference. The screws were inserted with a pneumatic screwdriver set to a specific torque.

The initial microscopic examination of the failed panels showed catastrophic transverse fractures within multiple cylindrical bosses on each of the parts. The cracking displayed features associated with brittle fracture, without appreciable macro ductility (Figure 1). No evidence of significant damage or abuse was apparent during the inspection.

The SEM examination of the panel boss fracture surfaces showed very consistent features, which were associated with brittle cracking. Multiple individual cracks were apparent, with distinct points of initiation along the inner diameter of the boss wall. The fracture surface within the origin zones displayed a relatively smooth surface texture characteristic of a slow crack initiation and growth mechanism. No evidence was found to indicate significant micro ductility. The crack origin areas were bounded by a series of band-like features (Figure 2), and at high magnification it was evident that these features represented opened craze remnants (Figure 3).

The fractures extended unidirectionally circumferentially from the crack origins around the boss. Crack unions were present, corresponding to areas where two individual cracks intersected. Isolated locations, remote to the crack origins, exhibited characteristics, including hackle marks and river markings, associated with rapid crack extension. These areas represented final fracture zones, and the observed features were consistent with mechanical overload, as the remaining ligament could no longer withstand the applied stress. A slight increase in the level of ductility was apparent within the final fracture zones.

No evidence was found during the fractographic evaluation to indicate post-molding molecular degradation, such as chemical attack or deterioration. Further, no signs of molding defects, such as voids or inclusions were apparent.

Together, the visual, microscopic, and SEM examinations indicated that the panel bosses failed via brittle fracture. The fractures were associated with the initiation of multiple cracks, leading to subsequent propagation and coalescence. The observed features were indicative of a slow crack initiation and growth mechanism, transitioning into more rapid crack extension remotely. Overall, the observed features were indicative of environmental stress cracking. Environmental stress cracking (ESC) is a failure mechanism whereby a plastic material cracks due to contact with an incompatible chemical agent while under tensile stress. It is a solvent-induced failure mode, in which the synergistic effects of the chemical agent and mechanical stresses result in cracking.

The requisite mechanical stress apparently resulted from stress imparted on the boss from the mating self tapping screw. This stress included longitudinal and torsional stresses from the fastening process, essentially pulling the boss axially, as well as hoop stress resulting from interference between the boss and the fastener. This situation was aggravated by the use of an improper, oversized screw, which increased the level of interference.

FTIR spectra were obtained on specimens representing failed parts, and the results indicated that the panels were produced from a polycarbonate resin. No signs of bulk contamination of the materials were indicated in the FTIR absorption spectra. However, analysis of the exposed boss fracture surfaces revealed a detectable amount of a residue. Comparison of the spectra representing the residue and the failed part material showed no indications that the residue was within the bulk of the compound, and thus was an external residue. The residue was identified as a paraffinic hydrocarbon oil, known to be a mild environmental stress crack agent for polycarbonate. Analysis of several screws, provided in the as-received condition, produced results that also indicated the presence of the hydrocarbon oil. This suggested that the sources of the hydrocarbon oil was a fluid used in the production or rust proofing of the screws. As such, in this case, the self tapping screws provided both the stress and the chemical responsible for the ESC failures.

Further analysis, including DSC, TGA, and melt flow rate testing, produced results characteristic of an unfilled polycarbonate resin. No evidence was found to indicate bulk contamination of the failed part material, or that the panel material underwent molecular degradation as a result of the injection molding process. Further, no signs of post-molding molecular degradation were evident.

Electronic Housing – Molded-in Insert

An electronic housing failed shortly after assembly, prior to being put into service. Cracking was observed within insert bosses associated with display mounts. Overmolded metal inserts were used to secure the assembly. The inserts were internally threaded and designed with a knurl and groove configuration. During the assembly process, the mating fastener was subsequently driven into the insert without the use of a torque-limiting driver. The housings were injection molded from an unfilled general purpose poly(acrylonitrile:butadiene:styrene) (ABS) resin.

The fractographic examination of the failed parts showed both transverse and longitudinal cracking. The fracture surfaces exhibited sharp and distinct features characteristic of brittle fracture, and no signs of significant macro ductility were found (Figure 4).

The SEM inspection revealed features indicating multiple crack origins around the inner diameter of the boss (Figure 5). The fracture surface within the crack origins presented a generally smooth surface texture. The origins were bounded by an increased level of micro ductility (Figure 6), indicating a relatively brittle fracture initiation that transitioned to increased ductility as the crack extended. Areas outside of the crack origins displayed significant levels of micro ductility, as indicated by the presence of stretched flaps and fibrils. These areas on the fracture surface also showed hackle marks and river markings, associated with rapid crack extension.

A cross-section was prepared through one of the bosses on an apparently uncracked reference part that had been molded and recently assembled, but not put into service. The cross-section (Figure 7) showed that the insert was designed with relatively sharp corners that acted as points of stress concentration on the formed plastic. Additionally, relatively small cracks were observed extending from the sharp corners. This indicated that cracking within the boss initiated shortly after installation of the display into the housing.

No evidence was found during the fractographic evaluation 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 apparent.

The sum of the fractographic examination observations indicated that the cracked housings failed via a mechanism that produced significant micro ductility, but lacked substantial macro ductility. The combined features observed during the fractographic examination were characteristic of an overload mechanism, corresponding to stresses that exceeded the short-term strength of the material. The combination of the brittle macro features and the ductile micro features was indicative of overload through a relatively rapid load application. The crack initiation sites were positioned at a corner in the boss wall formed by compliance with a sharp feature in the mating overmolded metal insert. This corner resulted in a significant stress concentration factor, thereby multiplying the applied loads.

Based upon the fracture surface features, the overload event that caused the cracking was the insertion of the screws into the threaded metal inserts, exacerbated by the stress concentration of the sharp corner. Once cracking initiated, thus relieving the immediate overload stress, a slow crack growth mechanism produced continued crack propagation over time, until the cracks grew to the point that they were observed externally.

Analysis of the housing sample produced results characteristic of an ABS resin, and no evidence was found to indicate bulk contamination of the failed part material. Melt flow rate testing did not indicate molecular degradation associated with the injection molding process. Further, no signs of post-molding molecular degradation were evident.

Machine Door Hinge – Rivets

Front access doors used on a newly designed piece of industrial machinery failed after production, but prior to scheduled engineering evaluations. Specifically, cracking was observed within hinges used to secure the door to the main body of the equipment. The hinges were fastened to the door using stainless steel rivets. The front access door was produced from an easy flow, unreinforced, flame-retardant, injection molding grade of polycarbonate / poly(acrylonitrile:butadiene:styrene) (PC+ABS).

The fractographic examination of the cracking associated with the rivets showed that the cracks were relatively consistent across all of the failed parts. The cracks were positioned adjacent to the rivet (Figure 8). From the exterior, the crack features lacked significant macro ductility, and instead exhibited characteristics of brittle fracture on a macroscopic level. Under optical microscopy, the fracture surfaces displayed further characteristics of brittle fracture (Figure 9). The observed features indicated crack initiation along the inner diameter of the rivet hole at a location adjacent to the mating rivet.

The SEM examination of the fracture surface revealed evidence of a single area of crack initiation along the inner diameter of the rivet bore. The crack origin area displayed a relatively smooth morphology, without evidence of significant macro ductility (Figure 10). The features were consistent with brittle fracture via a slow crack initiation mechanism. The origin was located immediately adjacent to some mechanical damage, thought to have resulted from the insertion of the rivet. The fracture surface adjacent to the crack origin showed an increase in the level of micro ductility, as indicated by an overlapping morphological structure, and the formation of stretched flaps. Indications of radiating bands were also present. Remote to the crack origin signs of rapid crack extension, including hackle marks and river markings were present, indicating a transition from slow crack growth to rapid crack extension (Figure 11). This portion of the fracture surface represented overload of the plastic material when the remaining ligament could no longer withstand the applied stress.

A typical failed area was examined cross-sectionally in order to more comprehensively evaluate the cracking associated with the hinges. The rivet and the surrounding hinge was excised from the part, mounted cross sectionally, and polished to reveal the area of interest. Microscopic examination of the prepared cross-section showed the presence of cracking that was not externally visible (Figure 12). The cross sectional examination showed that the crack origins observed during the microscopic inspection corresponded to a mechanical feature in the metal rivet. It was apparent that the rivet exerted stress onto the mating plastic.

From the fractography, it was concluded that the cracks within the hinges associated with the rivets were created via slow crack initiation and growth through a creep rupture mechanism. Creep is a phenomenon that occurs within plastic materials as a consequence of relatively low stresses continuously applied over an extended period of time. Creep is the result of the polymer molecules slowly disentangling over time, and causes the material to slowly strain until failure occurs. This was most apparent in the cross-section produced on the boss from the as-molded part, which showed cracking extending from the metal insert. Crack initiation sites were positioned at sharp corner features in the rivet. These corners acted as a significant stress concentration factor, thereby, multiplying the applied loads producing stress that exceeded the long-term strength of the material.

Melt flow rate testing of the failed part material produced results indicating excessive molecular degradation associated with the injection molding process. Molecular degradation represents reduction in the molecular weight of the polymer, and diminishes the mechanical integrity of the molded part. This molecular degradation is thought to be a contributing factor in the cracking of the front access doors.

Analysis of the door material through FTIR and DSC produced results characteristic of a PC+ABS resin. No evidence was found to indicate bulk contamination of the failed part material. Further, no signs of post-molding molecular degradation were evident.

Electronic Control Knobs - Shaft Spring

A significant number of control knobs used on a piece of consumer audio electronic equipment failed while in service. The control knobs were injection molded from a standard unfilled, platable grade of polycarbonate / poly(acrylonitrile:butadiene:styrene) (PC+ABS). The parts were subsequently plated with a brushed metal finish. As assembled, the electronics knobs were used in conjunction with a carbon steel shaft spring to secure the parts to the mating controller shaft.

The failed parts were visually and microscopically examined. The knobs exhibited cracking at consistent locations, at a design corner within the bore that interfaced with the mating controller shaft (Figure 13). The cracking was uniform across the received parts in regards to location and form. The cracks did not present signs of significant macroductility, and conversely, exhibited features characteristic of brittle fracture. Continued inspection revealed features indicative of crack initiation along the inner diameter of the knob bore wall. Importantly, a significant level of mechanical damage was apparent on the inner diameter surface of the bore immediately adjacent to the crack origins. This damage was present as gouging and material loss to both the plastic substrate and the metal plating.

SEM examination of the fracture surface confirmed crack initiation along the inner diameter of the bore wall. Multiple individual crack origins were present along the inner diameter surface. The individual crack origins were separated by ridge-like features representing crack unions (Figure 14). As identified during the microscopic examination, the crack origins were immediately adjacent to areas of substantial mechanical damage to the knob bore inner diameter surface. The cracking appeared to result from the damage. The surface within the crack origin areas displayed evidence of moderate micro ductility, in the form of stretched fibrils and flaps. Examination of the origin areas at higher magnification revealed the presence of a series of linear stretched fibril and flap formations perpendicular to the crack propagation direction (Figure 15). These features were consistent with a progressive failure mechanism associated with repeated cracking and arrest, such as dynamic fatigue.

Examination of mid-fracture locations on the crack surface showed a thumbnail marking representing a transition within the crack propagation mechanism. Outside of the thumbnail marking extending to the outer diameter of the bore wall, the fracture surface showed features, including river markings and hackle marks, characteristic of rapid crack extension and mechanical overload.

Further SEM examination was conducted on the area of the knob bore exhibiting mechanical mutilation. The damaged area exhibited substantial gouging and material loss, as well as tearing. This inspection of the damage also showed that the crack origins extended immediately out of the damaged surface area.

Throughout the 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 apparent.

The entirety of the visual, microscopic, and SEM examinations indicated that the control knobs failed via a mechanism associated with no macro ductility, but moderate level of micro ductility. The cracking initiated along the inner diameter surface of the knob bore, and subsequently propagated through the bore wall. The observed features were indicative of crack initiation associated with significant mechanical damage to the inner diameter surface caused by the inserted metal shaft spring. Movement of the spring, and in particular the sharp edge of the retention feature (Figure 16), resulted in gouging and damage to the inner diameter surface. This damage produced a significant stress concentration, in addition to the stress concentration associated with the corner design. The localized stresses subsequently exceeded the strength of the material and cracking initiated. Crack propagation occurred through a progressive mechanism associated with the repeated actuation of the knob during use. Given the relative level of micro ductility and the spacing of the stretched linear fibril indications, crack propagation was thought to occur through low cycle fatigue, meaning less than 10,000 cycles, and likely significantly fewer. Once the cracking progressed sufficiently through the part wall and the exerted stress exceeded the strength of the remaining ligament, the fracture transitioned to rapid crack extension through mechanical overload.

Analytical testing of the knob material using FTIR and, DSC produced results characteristic of a PC+ABS resin blend. No evidence was found to indicate molecular degradation, such as chemical attack or thermal deterioration of the knob material. Further, no signs of contamination or other formulation anomalies were found.

Discussion

Through the failure analysis process, particularly fractographic examination, it is possible to understand the impact of metallic fasteners on mating plastic components. The presented case studies illustrate the diversity of failures that can result from the interaction between metallic fasteners and plastic components. In particular, the presented case studies showed:

- Environmental stress cracking associated with residual chemicals on the metal fasteners and stress imparted by self tapping screws
- Mechanical overload resulting from excessive stress from the insertion of screws and the transfer of stress to the plastic boss
- Creep rupture produced by continuous static stress associated with interference between rivets and the mating plastic, exacerbated by stress concentration from the fastener's sharp corner features
- Mechanical damage generated by sharp features on metal shaft springs that lead to fatigue failure through repeated actuation

The primary factors prevalent in the failures were:

- Sharp corner features within the fastener acting as points of stress concentration
- Extended time under continuous levels of relatively low stress associates with interference between the fastener and the plastic
- High strain rates associated with assembly or insertion of the fastener
- Cleanliness of the metal fastener resulting in chemical exposure

In most cases, these are not a concern with complete metal assemblies, but can be major issues with plastic.

In reviewing the performance of plastic components in conjunction with metal fasteners, the following are of great importance:

- Type of plastic and complete formulation, including additives and modifiers
- Notch sensitivity of the plastic resin
- Fastener type and design
- Design of the plastic components, including hole sizing and tolerance consistency
- The level of interference and residual stress imparted onto the plastic
- The installation process, especially the rate of insertion and the force exerted
- Cleanliness of the fastener

Great consideration needs to be taken in matching the fastener with the application in order to provide the best performance and avoid premature failure.

A type of failure not illustrated in the case studies is pullout failure, in which the fastener, particularly an insert, loosens within the plastic and is pulled out by the applied load. This failure is primarily driven by stress relaxation, and pullout occurs when the applied load exceeds the interference stress between the plastic and the fastener. This is the primary failure mode considered by fastener manufacturers, and the focus often is in selecting the proper fastener to obtain higher strip-out torque values, increased resistance to loosening, and higher pullout values.

> "A common problem with bolted joints is that plastics are susceptible to creep or stress relaxation. Under loads well below the elastic limit, plastics will lose their ability to maintain a load. When this occurs, the threaded connection becomes loose."[3]

However, in many cases this focus results in the types of failures documented in this paper. Often, the characteristics that give a fastener superior resistance to pullout failures result in elevated stress concentration leading to short-term overload failures or long-term creep rupture. The interference stress imparted by mechanical fasteners, exacerbated by sharp corner stress concentration and mechanical damage, commonly produces creep rupture failure. It is well documented that static strain conditions, such as those associated with metal fasteners, can produce cracking within the mating plastic part.[4]

References

1. Austin Weber, New Techniques for Joining Plastic to Metal, Assembly Magazine, September 3, 2014,
2. Christie Jones, Tips and Techniques: How to Get Best Results With Insert Fasteners, Plastics Technology, October, 2010
3. Christie Jones, Tips and Techniques: How to Get Best Results With Insert Fasteners, Plastics Technology, October, 2010
4. Jeffrey Jansen and Jake Nemec, Creep Rupture Failure Under Conditions of Static Strain, ANTEC 2014

Keywords

fastener, joining, failure analysis, fractography

Fig. 1 - The fracture surface from one of the failed panel bosses is shown exhibiting features characteristic of brittle fracture. Multiple individual crack origins are present around the inner diameter of the boss.

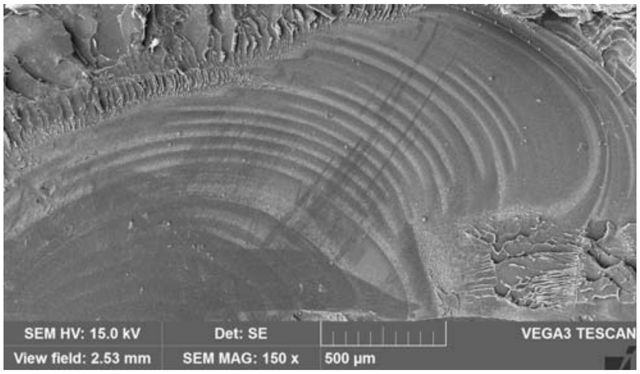

Fig. 2 - SEM micrograph showing a series of band-like features radiating from the crack origin.

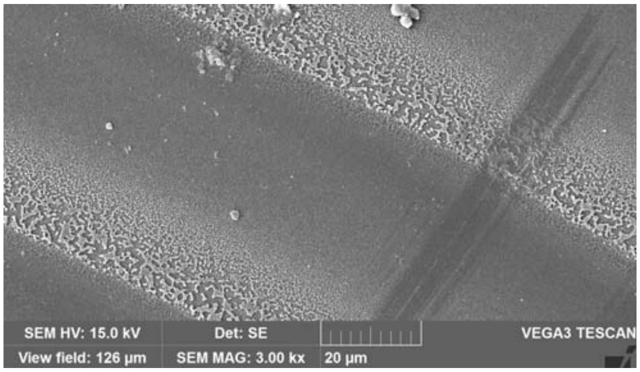

Fig. 3 - SEM micrograph showing that the band features represent a series of opened craze remnants.

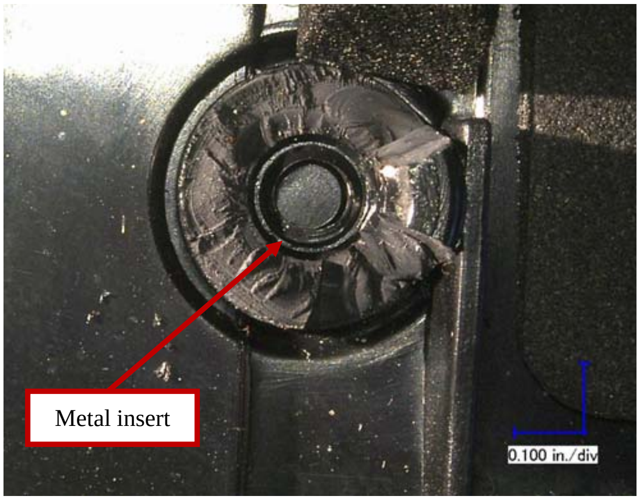

Fig. 4 - The fracture surface of the housing insert boss is shown exhibiting brittle fracture features, without apparent macro ductility.

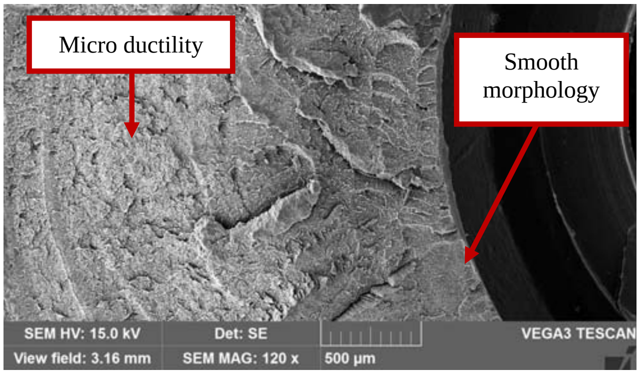

Fig. 5 - SEM image showing the presence of multiple crack origins around the inner diameter of the boss. The fracture surface transitioned from a relatively smooth surface to one exhibiting more ductile characteristics.

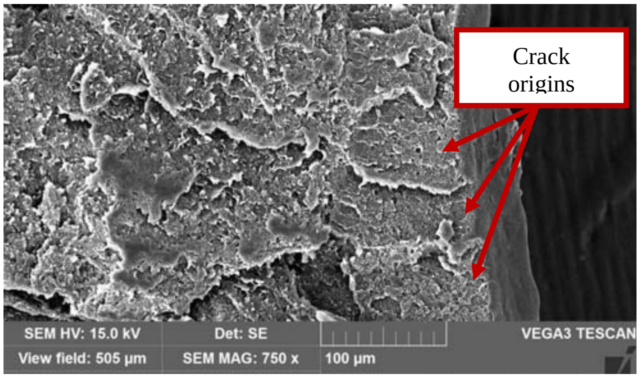

Fig. 6 - SEM image showing significant micro ductility immediately adjacent to the crack origins.

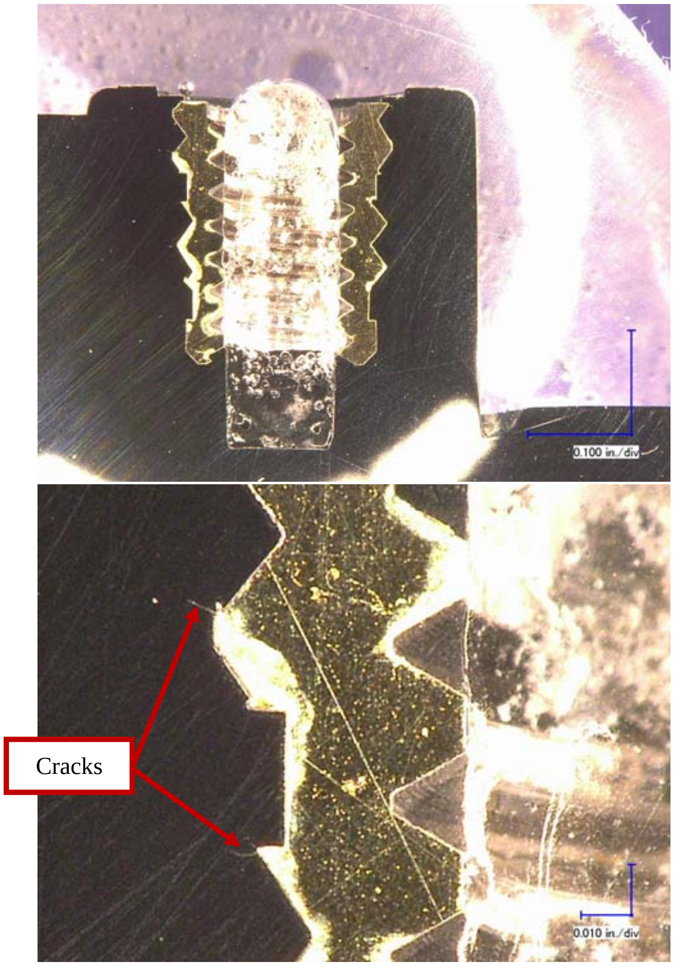

Fig. 7 - The cross-section prepared through the insert exhibited cracking within the boss material. The insert is designed with relatively sharp features, and the cracks extend from these corners.

Fig. 8 - Cracks were present adjacent to the door hinges. The cracking shows no signs of significant macro ductility.

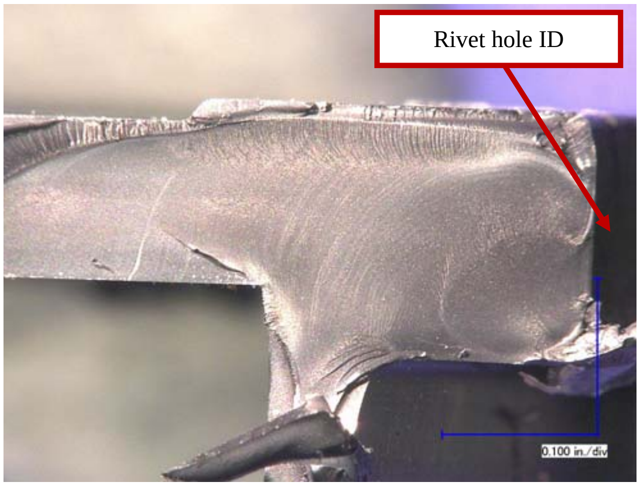

Fig. 9 - The fracture surface exhibits a relatively smooth surface texture indicative of brittle fracture. The features indicate crack initiation along the inner diameter of the rivet hole.

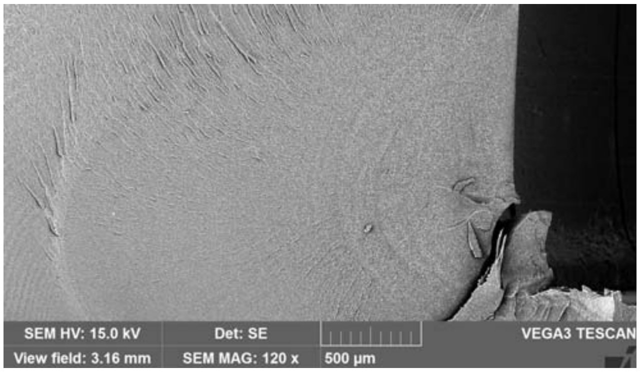

Fig. 10 - SEM micrograph showing a very smooth surface morphology at the crack origin indicative of brittle fracture through slow crack growth.

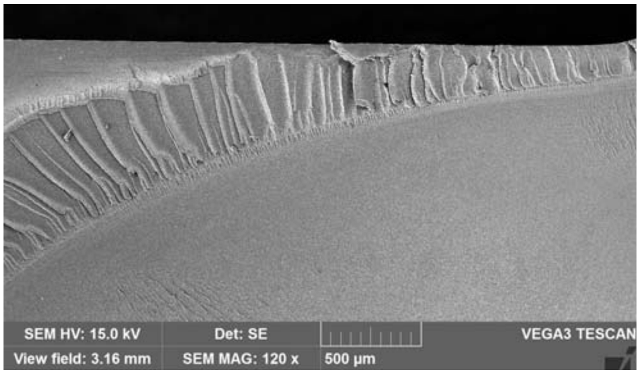

Fig. 11 - SEM micrograph showing the transition from a smooth surface morphology representing slow crack growth to features, including hackle marks and river markings associated with rapid crack extension.

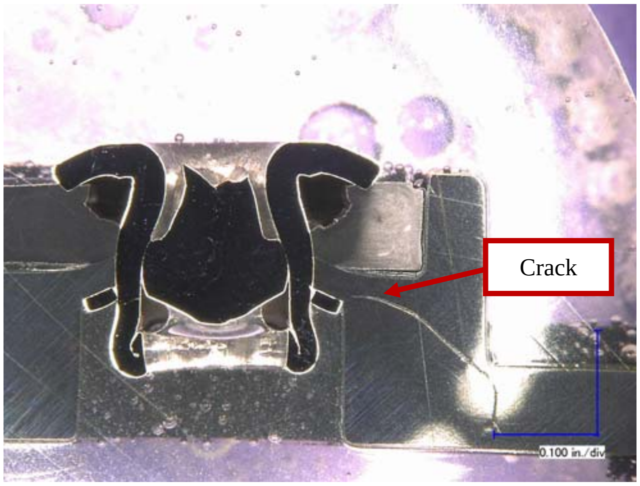

Fig. 12 - The cross-section prepared through the riveted hinge showed that the cracking extended from relatively sharp edges within the metal fastener.

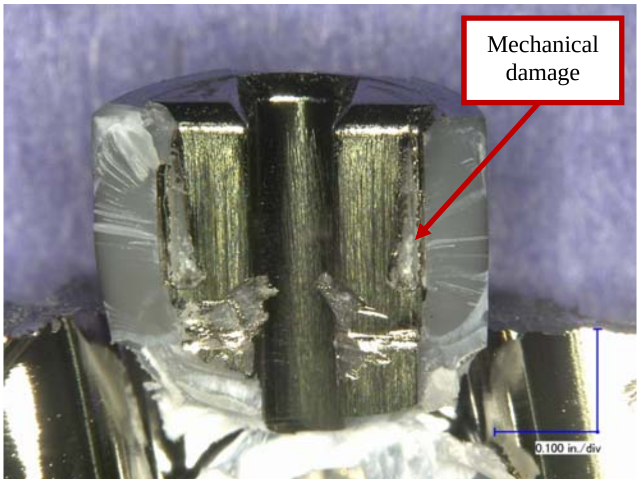

Fig. 13 - The cracking within the knobs did not show signs of significant macro ductility. The crack origins were positioned along the inner diameter of the knob bore wall.

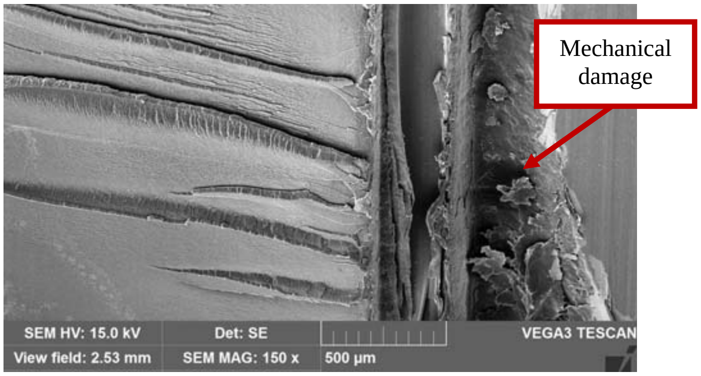

Fig. 14 - SEM micrograph showing crack initiation along the inner diameter of the knob bore wall adjacent to substantial mechanical damage caused by the shaft spring. Ridge-like features representing crack unions are present.

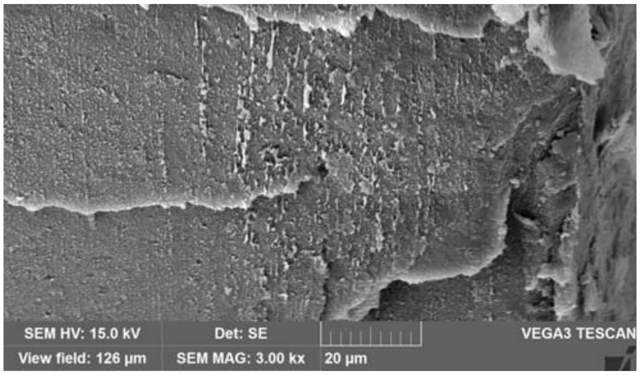

Fig. 15 - SEM micrograph showing linear stretched fibril and flap formations.

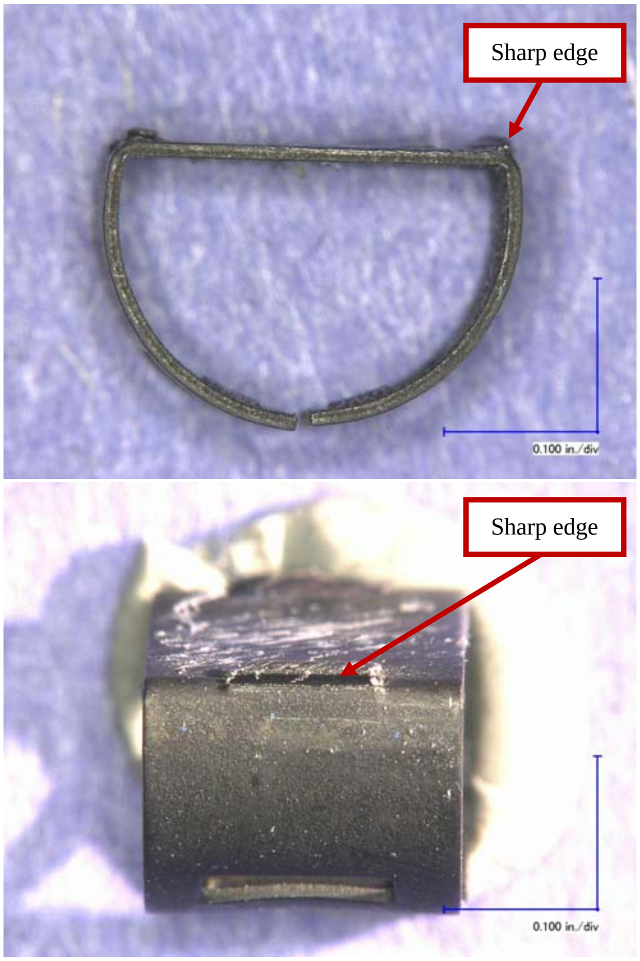

Fig. 16 - The shaft spring exhibited sharp features that produced mechanical damage along the inner diameter of the knob bore wall.