

# Die Performance Optimization through Understanding of the Surface Features of Fatigue Fractures

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**ABSTRACT** --- The analysis of failures of extrusion dies is a very important aspect of extrusion die manufacturing. Establishing the cause of failures provides information for improvements in design, materials selection, operating procedures, and the use of components. Understanding how to interpret observed surface features of fatigue fractures provides a basis for meaningful results. In this paper the emphasis is placed on the macroscopic fracture surface appearance associated with known loading conditions. The fracture face can provide a range of information about the causes. It can show the type and direction of the forces acting on a die, the magnitude and fluctuations of these forces, and can give a general indication of the length of time from initiation to final fracture. Several case studies are described in detail. These studies deal with real failures, in which the scope of the failure analysis was limited by factors such as the time that could be devoted to the problem, the expense of the testing desired and particularly incomplete information about the failure situation. Despite these limitations very valuable information was gathered and findings were implemented into modern extrusion die manufacturing processes.

## INTRODUCTION

Manufacturing defects, operating errors and unforeseen events all have an impact on extrusion die service life. To optimize the service life of a given tool, failures should be understood and minimized in all manufacturing and extrusion process steps and proper tool use must be ensured. Failure is a general term used to imply that a part in service (1) has become completely inoperable, (2) is still operable but is incapable of satisfactory performing its intended function, (3) has deteriorated seriously, to the point that it has become unreliable or unsafe for continued use<sup>[1]</sup>. About 70 percent of all tool failures are due to fracture. Of the remaining failures, about 10 percent were due to wear, cold-weld phenomenon and other causes<sup>[2]</sup>. Fracture is the irregular surface produced when a piece of metal is broken. The fracture face can provide a range of information about the causes, and therefore can significantly contribute to the improvement of tool service life.

## Visual Examination and Fractography

Fractography is the term coined by Carl A. Zapffe in 1944 following his discovery of a means for overcoming the difficulty of bringing the lens of microscope sufficiently near the uneven surface of a fracture to disclose its details within individual grains<sup>[3]</sup>. The purpose of fractography is to analyze the fracture features and to attempt to relate the topography of the fracture surface to the causes and / or basic mechanism of fracture.

Broken hot aluminum extrusion dies come in all shapes and sizes, and they are used in many different environments, which complicate interpretation of failures. An extrusion die that was used and then stored in a moist or high-temperature environment with heavy corrosion deposits can sometimes be more challenging to evaluate than one that was used and stored in a dry environment. Yet, some fracture surface "contaminations" give helpful clues about how the crack started and grew and how long it took to grow. The specialist in extrusion die fracture analysis can often see things that are not obvious to someone who has not studied fractography.

Not many published work is available in the area of the hot aluminum extrusion die failure analysis where fracture face is methodically described. Jung et al.<sup>[2]</sup> documented the various types of tool failure occurring from design through the application stages with special focus on heat treatment related failures however no detailed fracture face analysis is included. Analysis of many fractured dies presented by Arif et al.<sup>[4]</sup> leads to some very exciting conclusions, such as fatigue fracture being the principal failure mode for solid dies, wear and deflection being almost equally responsible for hollow die failures, and all the three major failure modes contributing almost evenly to breakdowns of semihollow dies. Again, Arif's analysis does not include any reference to the fracture face evaluation.

Fortunately, the features of the broken parts itself provide clues as to what types of stresses were really present. It is not always possible to know for sure exactly what types of stress were present, but even in these cases; it is often possible to know what stresses did not cause a particular crack to happen. In summary, visual examination and fractography give specialist the tools to determine whether or not the die design appears to be basically sound. Other features can give an idea about whether a manufacturing problem has created a brittle material where a ductile material would have been expected. Brittle materials tend to be much less forgiving of usual operating conditions than ductile ones. Still other features can shed light on whether an excessively sharp fillet at a section change is creating higher stresses than necessary.

### Fatigue Fracture Surface Features

Fatigue fractures are the most commonly identified kinds of failure of structural metals. The term fatigue is an appropriate one, for it refers to the time-delayed fracture of materials subjected to cyclical stresses below those causing plastic yielding and / or tensile failure. In order for a fatigue failure to occur, at least some portion of a time-varying stress must be tensile in nature. That is, a stress state for which the maximum principle stress is always algebraically negative (compressive stress) does not lead to fatigue fracture.

As with most fracture, fatigue fracture involves crack nucleation, growth, and "coalescence." Crack nucleation in fatigue, as in most ductile fracture processes, is related to non uniform plastic flow occurring (usually) at a microscopic level, and such flow can take place even when a structure is only elastically stressed in a macroscopic sense. Fatigue cracks in metals originate almost exclusively at internal or external surfaces, the latter being more common. In all materials there are regions of local heterogeneity that result in local "softening" or surface flaws that cause local stress concentration. With cyclic loading at tensile stress below the yield strength, a crack will begin to form at the region of greatest stress concentration after some critical number of cycles. With continued cycling, the crack will grow in length in a direction perpendicular to the applied tensile stress. After the crack has progressed a certain distance, the remaining cross-section can no longer support the loads, and final rupture occurs.

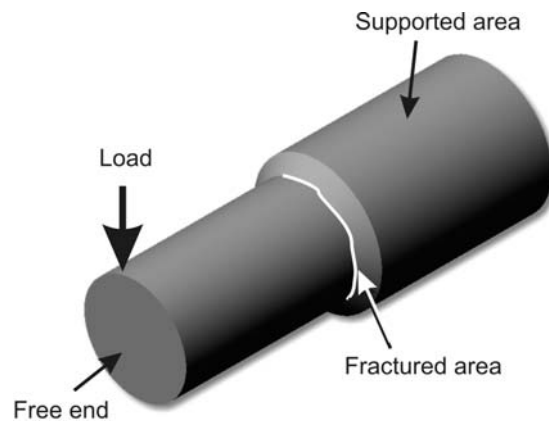


Figure 1. Illustration of loading conditions acting at mandrel's free end

In most extrusion dies used for hollow profiles extrusion the mandrel is subjected to bending. The bending is a result of non uniform pressure applied to the mandrel caused (among many factors) by not

perfectly balanced metal flow within welding chambers. Moreover, if the die bearings are of different length all around the mandrel the pressure generated on them due to friction during hot aluminum extrusion is also non uniform leading to some mandrel bending. In Figure 1 simple mandrel subjected to bending is presented. Force is applied to its free end while the other end is fully constrained. During extrusion process the mandrel is repeatedly bend and released. Fatigue fracture face observed on similar mandrel manufactured with very brittle material and subjected to cyclical bending due to non uniform bearing length is presented in Figure 2.

Macroscopically, a fatigue fracture is flat and perpendicular to the stress axis with the absence of necking. Part of the fracture face is slowly cyclically grown (see Figure 2 – left), but the remainder occurs by overloading, that is one step fracture. The most distinct characteristic of fatigue failures in the filed are the beach or clamshell markings on the cyclically grown portion of the fracture (see Figure 2 – right). The distance between the “ring markings,” macroscopically visible on the fracture face, is not a measure of the crack advance per stress/strain cycle. Since fatigue failures typically occur only after many thousands (sometimes millions) of such cycles, it is clear that the slowly growing crack advances only microscopic distances per cycle. Beach marks document the position of the crack front at various arrest points during its growth.

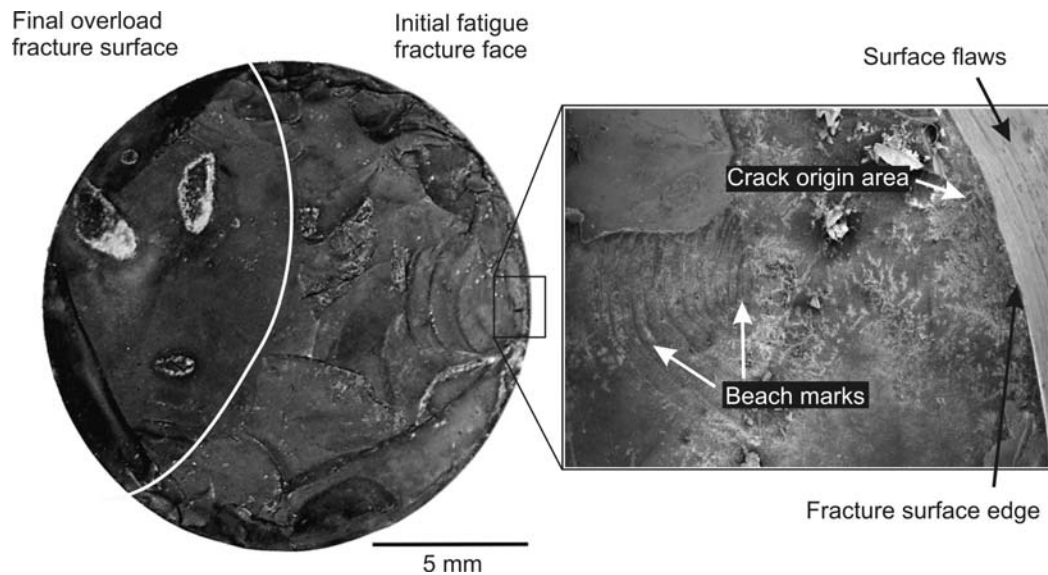


Figure 2. Fracture surface of a fatigue failure showing fine beach marks (SEM image – right)

The example in Figure 3 can be used to illustrate the effect of the load level (stress level) on the fractographic features. If the load is relatively low, then it takes many cycles for the fatigue crack to propagate to a location where the remaining material will fracture catastrophically on the next (and final) load application. Thus the relative amount of the fracture surface covered by the beach marks will be large. If the stress level is high, then the crack will not propagate far before final fracture occurs<sup>[5]</sup>.

The presence of beach marks is fortunate, at least for the investigator, because beach marks permit the origin to be easily determined and provide the analyst with other information concerning the manner of loading, the relative magnitude of stresses, and the importance of stress concentration. In this case one can say that the mandrel cross-section design is correct because it withstood applied loads even half cracked before final rupture occurred. It is also important to notice that crack very likely started at one of present surface flaws (see Figure 2 – right for details).

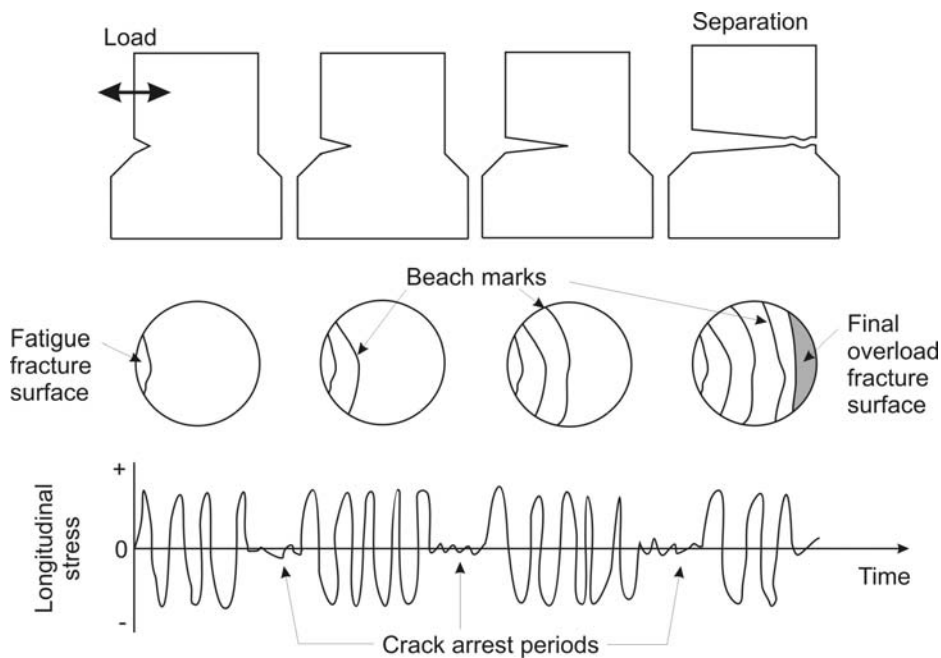


Figure 3. Schematic illustration of the formation of beach mark in a fatigue test<sup>[5]</sup>

One must remember that the presence of clamshell markings and /or striations is *per se* evidence only of not continuous crack growth, and does not necessarily mean that the failure is caused by fatigue of the kind discussed here. Consequently, while it is reasonable in many cases to identify fatigue as a cause of failure on the basis of the presence of clamshell markings, this should not always be done.

### Brittle Fracture Surface Features

Brittle fracture is fracture that involves little or no plastic, or permanent, deformation. Brittle metals like hardened tool steels are in daily use as normal engineering materials, and, as long as they are properly handled, they are very satisfactory for many types of service. In general, it is characteristic of very hard, strong, notch sensitive metals to be brittle, although research work attempts to raise useful strength of these metals without the danger of brittle fracture. Steels used for extrusion dies differ from most other steels in several aspects. First, they are used to extrude other products with aluminum. Second, dies are generally used at higher hardness than most other steel products. These high hardness requirements are needed to resist anticipated service stresses and to provide wear resistance. However, the steels must also be tough enough to accommodate service stresses and strains without cracking.

Brittle fractures have certain characteristics that permit them to be properly identified:

1. There is no gross permanent or plastic deformation of the metal in the region of brittle fracture, although there may be permanent deformation in other locations where relatively ductile fracture has occurred.
2. The surface of brittle fracture is perpendicular to the principal tensile stress. Thus the direction of the tensile stress that caused the fracture to occur can be readily identified.
3. Characteristic markings on the fracture surface frequently, but not always, point back to the location from which the fracture originated.

Hot aluminum extrusion dies are used while encapsulated by die ring on their outside and bolster at their exit side (see Figure 4 for details). In other words the dies are highly constrained tools working under different stress conditions. On the other hand, it is somewhat easier to predict stresses type and their concentration areas within highly constrained tools since there are very little not supported surfaces.

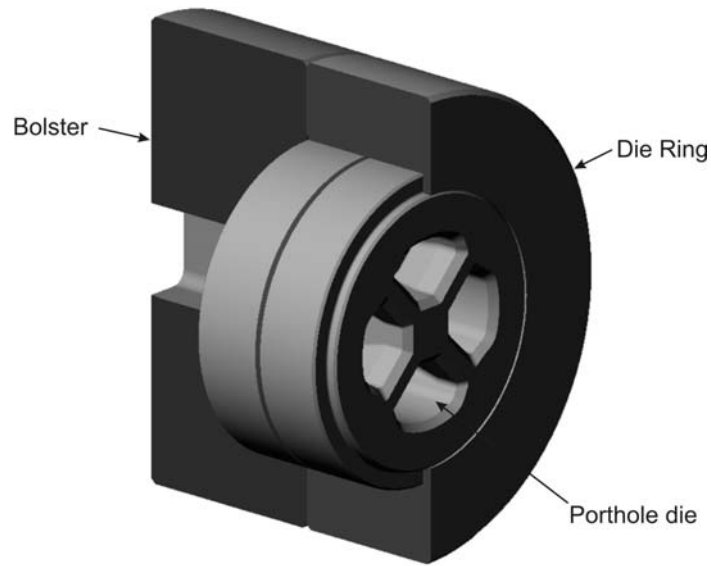


Figure 4. Partial section view of typical hollow profile tooling with pothole die encapsulated by die ring and supported by bolster

Presented in Figure 5 is porthole die cap with a continuous crack at one side and a crack arrested at the bolt hole on the other side. This part was run under standard extrusion conditions and it was not a first die manufactured for this profile. All of extruded products were dimensionally correct and no press problems were reported at the time of extrusion. After removing the die from the press it was cooled down to room temperature and put into caustic bath to remove aluminum. Time and temperature of the caustic bath were also at their nominal parameters. After the bath all of its residues were cleaned and the die was disassembled for inspection. A die technician inspected that die for any die lines, cracks, foreign object damages and did not notice potential problems. The disassembled die was nitrided following established procedures. Cracks in the die plate were observed upon its removal from the nitriding unit. The die plate did not drop during nitriding.

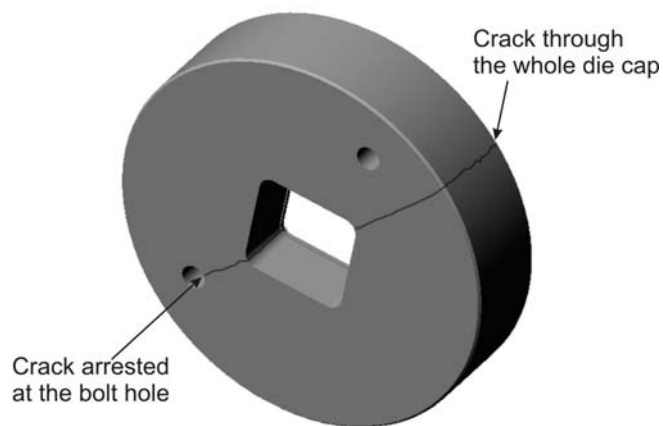


Figure 5. Illustration of cracks observed on die cap – one crack propagated through the whole part while the other was arrested at the bolt hole

After initial inspection of cracked die plate its part containing fracture face was cut out for further investigation (see Figures 6 and 7 for details). Fracture face presented in Figure 7 shows all attributes of brittle fracture face. This face is characterized by very little plastic deformation and by radial ridges that emanate from the crack origin area at the right edge of the fracture surface. The ridges, also called river marks, run parallel to the direction of crack propagation, and a ridge is produced when two cracks that are not coplanar become connected by tearing of the intermediate material. The cracks, which propagate predominantly by quasi-cleavage, move rapidly toward the periphery of the die plate cross-section and penetrate the external surface of the specimen by shear rupture along a relatively small shear lip. The shear lip develops as a result of the change in the state of stress from one of tri-axial tension to one of plane stress. The extent or width of the shear lip depends on the temperature at which fracture occurs, formation of shear lip being favored by higher temperatures. Higher fracture temperature also promotes the formation of readily visible river pattern. Therefore, the absence or presence of a ridge pattern on the fracture surface of a brittle fracture can be used to provide a qualitative estimate of the fracture temperature relative to the nil-ductility transition temperature of the steel. It is also important to note that about half of observed fracture surface between fracture origin and its middle area was covered with sand particles embedded between ridges. These particles were embedded during nitriding process.

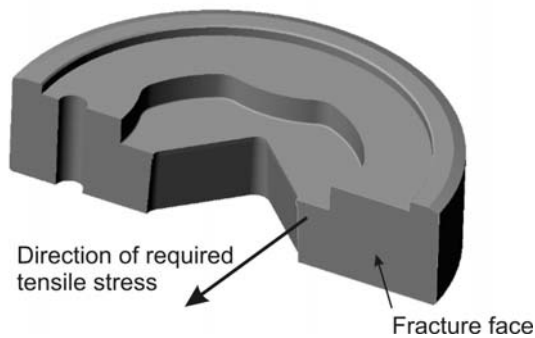


Figure 6. Illustration of location of evaluated fracture face

As note above, the brittle fracture shown in Figure 7 terminates with medium shear lip. This fact is helpful when attempting to determine the origin of a brittle fracture. The origin of the fracture is invariably characterized by the absence of a shear lip, whereas a shear lip is expected to be present along the periphery of the fracture surface where the crack emerges from the interior of the material. Consequently, the periphery of a fracture surface should be examined with these facts in mind. If fracture occurs at a low temperature, then the shear lip may not be formed.

As stated at the beginning of this paper fracture face analysis is a useful tool to distinguish between different fracture types however more effort is required to determine fracture cause(s) and its sequence. The factors that must be present simultaneously in order to cause brittle fracture in tool steel are as follows<sup>[6]</sup>:

1. *A stress concentration must be present.* This may be a weld defect, a fatigue crack, a stress-corrosion crack, or a designed notch, such as a harp corner, thread, hole, or the like. The stress concentration must be large enough and sharp enough to be a “critical flow” in terms of fracture mechanics.
2. *A tensile stress must also be present.* This tensile stress must be of magnitude high enough to provide microscopic plastic deformation at the tip of the stress concentration.
3. *The temperature must be relatively low for the steel concerned.* The lower the temperature for given steel, the grater the possibility that brittle fracture will occur.

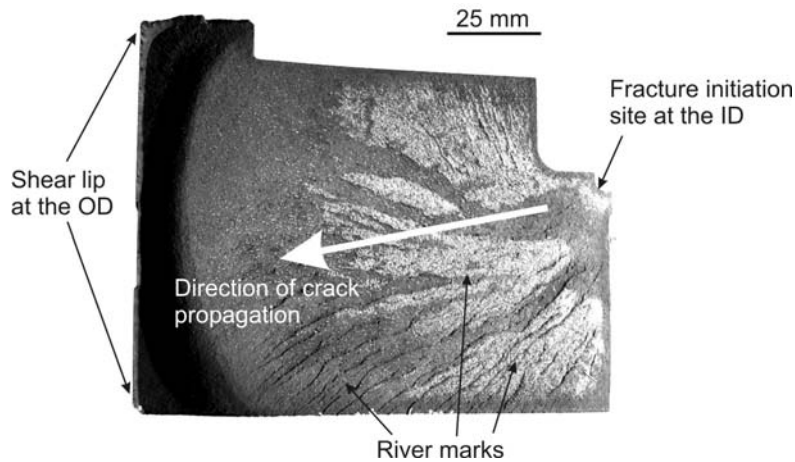


Figure 7. Brittle fracture in a porthole die cap  
(Note the pronounced radial marks indicating the fracture direction.)

The observed brittle fracture initiation site is marked in Figure 7. That area is very close to the bearing under cut and could be classified as a stress concentrator required for the brittle fracture to begin. The tensile stresses present at this area are generated by friction between hot aluminum flowing over the die bearing and are parallel to the fracture face, while the direction of tensile stresses responsible for this brittle fracture is perpendicular to the fracture face as illustrated in Figure 6. One could conclude that there must have been additional tensile stress acting at the same area and of magnitude high enough to initiate crack at the die bearing area.

During extrusion no forces are applied (on purpose) to the side of the tooling. The only force comes from aluminum being extruded and is acting from die center to outside. On the other hand the die is fully encapsulated within die ring as illustrated in Figure 4, thus the force generated by aluminum alone could not induce tensile stresses perpendicular to the analyzed fracture face. It is possible however that the tensile stress was a result of bending over the foreign object (like aluminum build up) sitting between die cap and bolster as presented in Figure 8. Die plate subjected to bending over such foreign object will develop the highest tensile stresses at the die bearing area. Below neutral plane the developed stresses will be compressive. Therefore, crack could arise at the die bearing area due to bending.

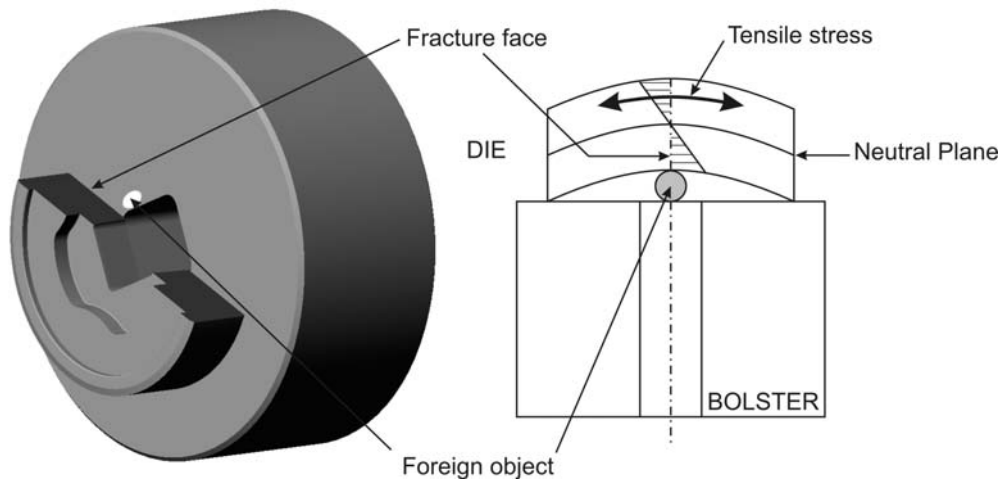


Figure 8. Illustration of die plate bending over the foreign object sitting between die cap and bolster  
(drawing no to scale)

The crack was not detected before nitriding because it did not propagate through the whole die plate cross-section. With increasing distance from crack origin area, the tensile stress intensity decreased; therefore there was not enough “driving force” for the crack to propagate. After extrusion and cooling to room temperature, the steel shrank, closing the existing crack tight while still constrained within the die ring. The cleaned and unconstrained die cap, subjected to high temperature during nitriding, expanded, letting sand particles between fracture faces. It is not clear when the final rupture occurred but it is possible that upon cooling to room temperature after nitriding, the die cap could not return to its original shape because of embedded sand particles and did crack.

## Summary and Recommendations

Failure analysis is a process that is performed in order to determine the cause of factors that have led to an undesired loss of functionality. Professionally performed failure analysis is a multilevel process that includes physical investigation itself and much more. Establishing the cause of failures provides information for improvements in design, materials selection, operating procedures, and the use of components. Understanding how to interpret observed surface features of fatigue fractures provides a basis for meaningful results. In this paper only two fracture modes were presented and discussed – fatigue and brittle. It was demonstrated that visual examination and fractography are useful tools for extrusion die and extrusion process improvement.

In this paper the emphasis is placed on the macroscopic fracture surface appearance associated with known loading conditions. The fracture face can provide a range of information about the causes. It can show the type and direction of the forces acting on a die, along with the magnitude and fluctuations of these forces, and can give a general indication of the length of time from initiation to final fracture. Most extrusion dies are subjected to some sort of bending or torsion loads in addition to any axial loads that they have. For this reason, surface-initiated cracks are more common than internal cracks. And again this reminds us of the importance of good machining practice. A smooth surface will often go a long way toward preventing fatigue cracks.



Figure 9. Aluminum buildup observed on die side face of bolster.

Analysis of brittle fracture observed on the die plate led to the conclusion that bending over a foreign object placed between die plate and bolster could produce enough tensile stress in the die bearing area to start the cracking process. In Figure 9 a witness mark of aluminum buildup on the die face of a bolster is presented. Aluminum could build up at this location as a result of shearing profiles between die and bolster before die change. It could also be a chunk of aluminum stuck to the die plate or bolster face during storage or handling. In both cases careful die / bolster interface inspection before extrusion could prevent this die cap from premature cracking.

## REFERENCES

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