

BARREL-WOUND MAINSPRINGS



Part 2: Why clock mainsprings fracture

by Guy Gibbons, OBE, MIMechE

The de Havilland Comet airliner

Readers of a certain age will perhaps remember the tragedies involving the World's first ever and perhaps most beautiful commercial jet-powered airliner, three being lost due to structural failure within the first 12 months of operation. Today, the reasons for their loss are better understood, but hitherto nobody had ever considered fatigue and fracture as a critical structural design criterion. Within a few years, the later Boeing 707 was one of the chief competitors to benefit from the new science.



One of a number of conclusions from the investigations was de Havilland's use of punched rivet holes rather than rivet holes produced by drilling. And as every clock repairer will know, the former tend to have ragged edges creating numerous out-of-plane (the through-thickness) direction crack initiation sites in the highly-stressed skin, the forensic Comet trials suggesting they could lead to catastrophic fracture within as little as a few thousand fatigue cycles. Drilled holes have smooth edges in the through-thickness direction.

And over half a Century later, what do horological authorities still recommend for creating holes in the primary horological component that suffers from fatigue failure, viz. the hooking holes at the outer ends of clock mainsprings?

You guessed it, punching.

The stresses at a hole

Figure 5 shows the stresses at a typical hole in a mainspring engaging with a peg in the barrel wall, the high stress regions being indicated by the lighter contours. Cracking will generally initiate and propagate from the high stress regions in one of two fracture modes (Figure 5 centre and right), and which occurs (transverse or longitudinal) is largely unpredictable as it depends upon a number of factors associated with the spring material and local (often microscopic) geometrical differences.

In a fully-wound mainspring, the field stress in bending at the outer surfaces is high for and may exceed the typical yield

stress of the material (up to 2000 MPa) as witness the mainspring's permanent set after first winding and unwinding. At the white (light) areas, the post-yield plastic deformation will be considerable and penetrate inwards from the surface right through the full thickness of the mainspring. Unavoidable on peg-and-hole hooking, localised plastic deformation will occur once on first winding, and providing the steel is not brittle (it has been tempered), fatigue crack initiation and propagation will generally not occur. But if it is subjected to repeated cyclic bending with sufficient crack-driving energy (strain energy), fatigue crack initiation and subsequent propagation will occur leading ultimately to fracture.

Fatigue

Engineers talk of three types of fatigue: low cycle fatigue (LCF), high cycle fatigue (HCF), and thermo-mechanical fatigue (TMF), of which we can discard the last as irrelevant for a mainspring in any normal environment.

- Low cycle fatigue: the local stress is taken into the post-yield plastic regime at each and every cycle. A typical low cycle fatigue life will be less than 1,000 cycles.
- High cycle fatigue: the local stress remains below yield at each cyclic loading, though it may well be taken into the post-yield plastic regime on first loading (first full winding). A typical high cycle fatigue life will be in excess of 10,000 cycles.

If a clock is designed for weekly going (an 8-day clock) with a design life of 20 years, the clock will see in the order of 1,000 repeated winding and unwinding cycles and the mainspring may just about get away without mainspring replacement (fracture) by designing for a low cycle fatigue regime. For a 20 year life, peg and hole hooking at the outer barrel end may just about be acceptable¹².

Conversely a 30-hour clock or wrist watch would see around 7,000 cycles over the same 20 year life, and if a fractured mainspring is to be avoided, it needs to operate in a high cycle fatigue regime so the mainspring remains in an elastic condition after the initial full winding. To an engineer, peg and hole

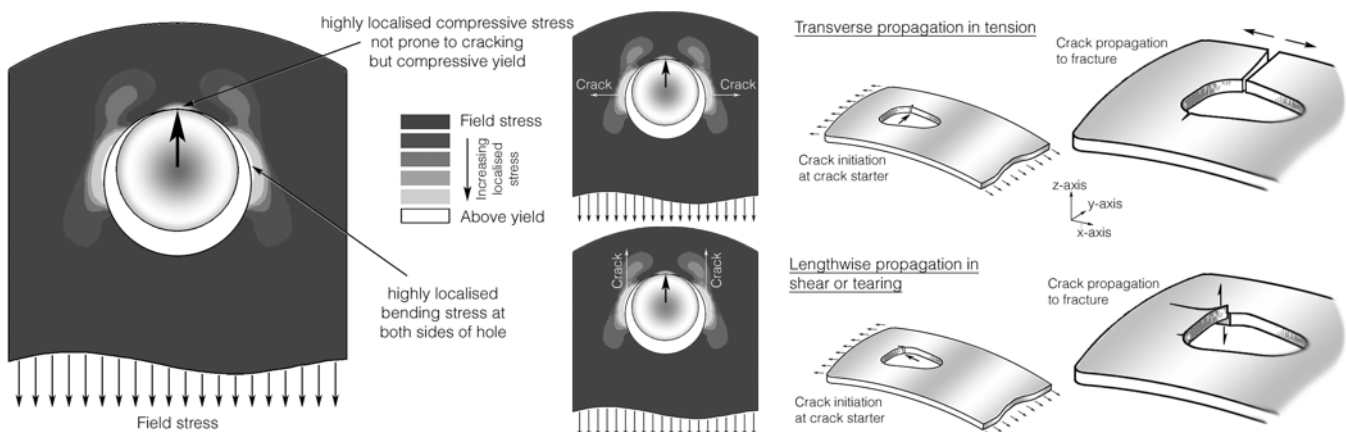


Figure 5: Typical stress distribution and fracture modes around conventional peg and hole barrel hooking.

hooking at the outer end will not be acceptable, and for this reason, such hooking is never found in modern watches.

It is rare for a crack to initiate at the inner mainspring hole (arbor end) as friction between the tightly-wrapped coils at the inner end relieves the arbor hook of most of the load as it nears the fully-wound high stress condition. Moreover, cyclic plastic bending does not take place as it does at the outer end hook – Figure 6, top right.

Common fallacies

Horological teaching authorities talk about ‘unbreakable’ mainsprings being made of ‘rustless’ materials, but let me assure readers that all mainsprings are breakable whether they are made from alloy steel, stainless steel or nickel-cobalt alloys. It is the geometry which primarily determines the fatigue life, not the material. Sure, corrosion (including rusting of ferritic alloys) may exacerbate fatigue crack initiation, but if one has corrosion inside a barrel one probably has other problems as well. For similar reasons one should always discard ‘new old stock’ mainsprings if rusted inside their wrapping paper.

Another fallacy is that plastic bending at the simple peg and hook can be avoided. Without up-stopwork it cannot, and this applies whether the barrel hook is a peg or a bent tab. Some authorities attempt to ameliorate this plastic bending by suggesting the spring can be forced to develop concentrically; unfortunately they fail to recognise that, without up-stopwork, mainsprings will be wound fully (hard up) rather than be partially wound as sketched by two authorities (Figure 6, left).

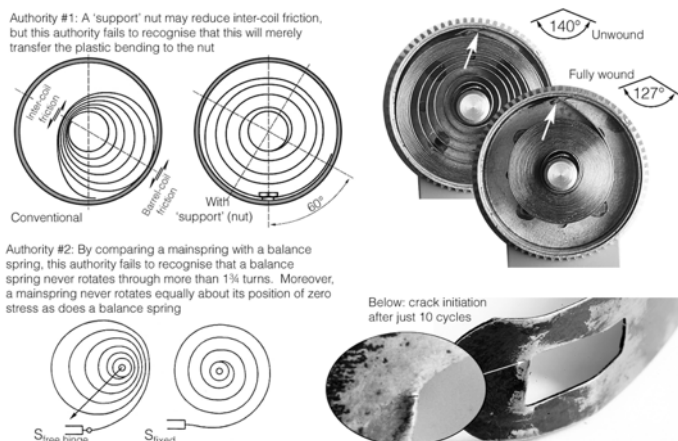


Figure 6: The fallacy of assuming that plastic bending can be avoided at conventional peg and hole barrel hooking. In the spring illustrated, a sharp 13° bend (140° – 127°, top right) will always be plastic as can be seen bottom right

To avoid low cycle fatigue (plastic bending), what one needs is to ensure the localised stresses on the end of the mainspring do not result in cyclic plastic bending as would occur when bending a paper clip back and forth.

The mechanism of fracture

In fracture mechanics, two stages are considered: crack initiation, and crack propagation. It is a hugely complex subject but, as a rule of thumb, the crack initiation phase is said to have completed when the crack is through-the-thickness (can be seen from both sides) and the length of the initiated crack is about the same as the material thickness. Thereafter, the crack is in the crack propagation phase, the available material to resist the applied stress ever decreasing as the crack propagates.

As previously mentioned, to initiate a crack requires some sort of geometric discontinuity either in the metallurgical structure of the material (inclusions, grain dislocations, etc.) or a discontinuity in the free surface (a sharp corner or notch caused by poor finish (eg. filing or punching in the through-thickness

direction)). Delaying the onset of crack initiation is best achieved by using the highest purity material and minimising surface discontinuities and surface roughness.

Once the crack has initiated, the rate of propagation is purely a function of the crack driving energy¹³ and the material properties (primarily toughness).

And in practical terms

The clock repairer has little choice in his or her selection of barrel hooking. If the mainspring hole must be punched rather than drilled, after filing to shape the edges should be draw-filed in the circumferential direction to remove all trace of file marks in the through-thickness direction, roughness and/or other discontinuity, and the corners well-radiused. Burnishing the edge of the hole in the circumferential direction may further delay the onset of crack initiation¹⁴.

A few examples of peg and hole mainspring failure are shown in Figure 7, and the only justification for their use is economy of manufacture coupled with an assumption that the owner has no requirement for an 8-day clock to last more than 20 years¹⁵. If a greater life is required, improvement is necessary, and consideration should be given to fitting a resilient hook.



Figure 7: Just a few examples of peg and hole mainspring failure

Overwinding

When bringing in a clock for repair, the customer will not infrequently say that he or she has overwound the clock. Some horologists claim that this is not possible – or is it?

If the mainspring is broken, it will generally be due to fracture in the vicinity of the outer eye. If the clock has not been gently brought to its fully-wound condition, the abrupt stop caused by over-vigorous winding will significantly increase the fatigue damage to the eye, and this can perhaps indeed be ascribed to ‘overwinding’.

Semantically, it all depends upon what one understands by the prefix ‘over’. It is self-evident that a mainspring cannot be wound over (beyond) full winding, but equally the eye of the spring can be subjected to a stress that is over the acceptable limit for low cycle fatigue.

Summary – Part 2

And the de Havilland Comet? Sure, mainspring fracture is at worst a gear-tooth stripping and finger bruising experience, but it always seems a shame not to learn from the hard-won experience (and deaths) of others. With the ready availability of diamond needle files and tungsten carbide twist drills¹⁶, is there really any excuse not to be attending to the raw edges of holes punched (or drilled) in mainsprings?

Overall, the writer has little doubt that the best form of barrel hooking is either the loop-end mainspring or the resilient hook,

the geometry of both being well able to cope with high cycle fatigue. It also suggests that the manufacturers of clocks with barrel-wound mainsprings might wish to consider fatigue design a little more seriously than they currently appear to do.

In Part 3, I shall discuss energy storage density before suggesting a possible statistical-based methodology for a preliminary estimate of the size of a mainspring for new design 8-day clocks based on chapter ring diameter.

12. For this reason, it is always advisable to renew clock mainsprings at all periodic survey, especially if one does not know the clock's (and hence mainspring's) usage history. See also note 4. An exception is low-yield mainsprings used in early fusee clocks, where the stress level is sufficiently low that low-cycle fatigue is unlikely to occur.

13. One fundamental requirement for crack initiation and propagation is an input of sufficient strain energy to drive the crack. This strain energy – and in particular the strain range through which the material is cycled – must be above the endurance limit, defined as the strain range below which the material may be taken through an infinite number of cycles without fatigue failure.

Due to the relatively poor-quality steels, 18th Century fusee clock mainsprings fitted with stopwork are necessarily low-stress devices that frequently do not exceed their endurance limit, which explains the survival of the 250 year old spring shown in Figure 4.

14. Essentially putting the surface skin into compression to reduce the tensile stress range, burnishing is a variation of the standard engineering technique of hammer- or shot-peening the surface to delay the onset of fatigue crack initiation.

15. If this were a motor car, a peg and hook mainspring would be treated as a component having a maximum safe life, the user manual recommending it be changed after (say) 10 years. And maybe clock repairers should also consider advising his or her customer much the same?

16. Not infrequently, the writer creates the mainspring hole with an HSS twist drill in the softened last few centimetres of a mainspring, accepting that it is expendable (blunt) after drilling each hole. Once drilled, the edges are shaped and draw-filed with a diamond file and the edges burnished with an oval burnisher.
