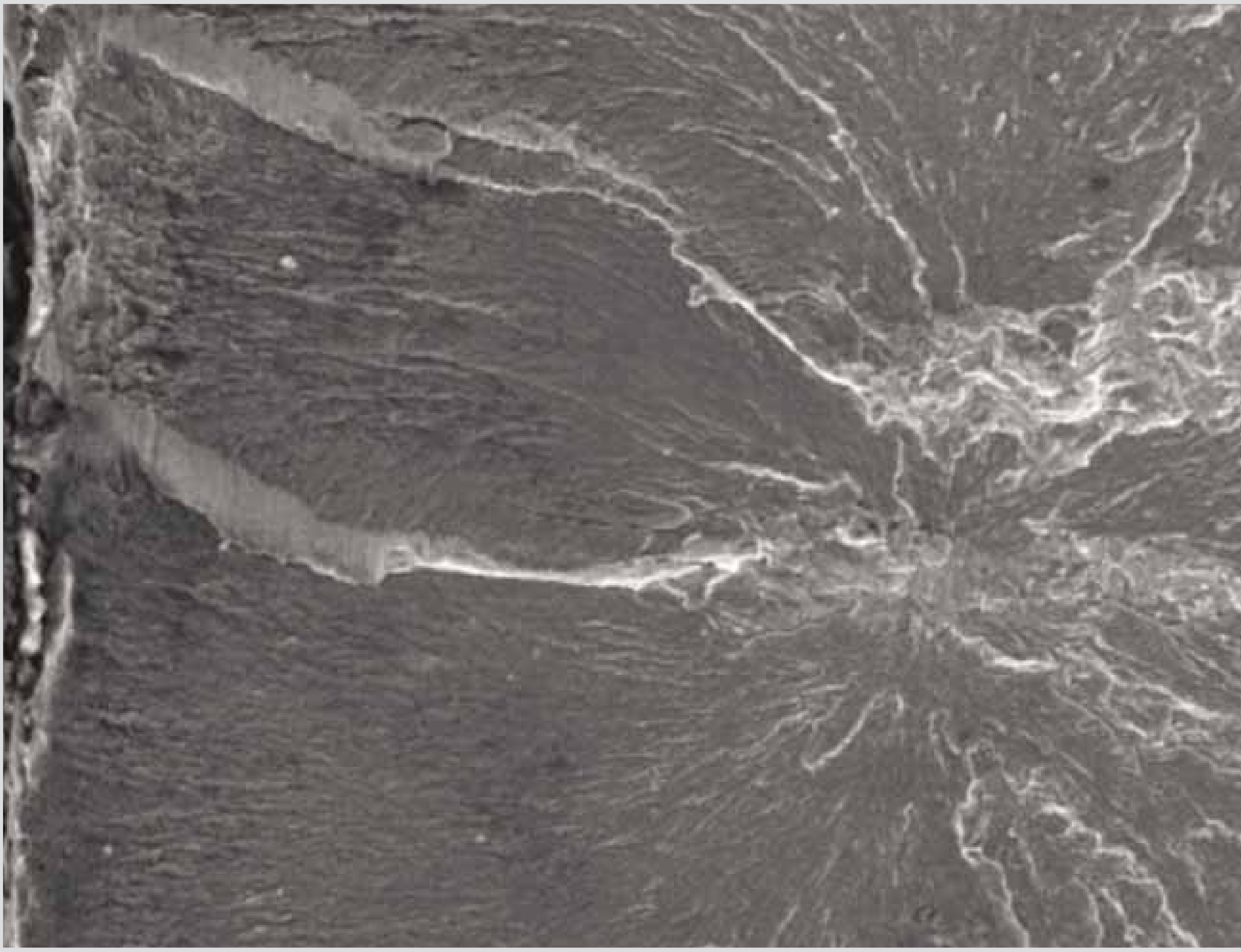


Process Optimization Through Failure Analysis

By Jason Sicotte, Associated Spring

The design goal of any spring is to absorb and return energy repeatedly without failure. Through years of experience, testing and data collection, it is fairly easy to estimate how many cycles a spring will survive before fracture for a given material grade and processing (i.e. stress relieving, shot peening, pre-setting, etc.). Inevitably, designers push the limits of stress for a given material and process, typically to optimize packaging or spring weight. In this situation, if a spring fails prematurely during testing, there is an opportunity to perform a detailed failure analysis — the results of which can be used to guide process optimization to improve durability.

In this article, Associated Spring, a world-class provider of engineered springs, provides a case history detailing how failure analysis can be used to optimize manufacturing processes for enhanced fatigue life.

In general, it is useful to consider the four inputs to fatigue life. In no particular order of importance, they include:

Figure 1: Stereo microscope image showing a classic fatigue halo.

1. Applied stress
2. Material fatigue resistance
3. Residual stress
4. Geometric stress concentrators

The intent is not to use these factors in a quantitative calculation, but rather to guide failure analysis and fatigue life optimization. These four factors can be further explained in the following ways:

- Applied stress includes the design stress, amplification from spring surge or dynamics, Hertz contact stress, etc.
- Material fatigue resistance includes tensile strength / hardness, microstructure, grain size, etc.
- Residual stress is the internal stress imparted by forming, heat treating, shot peening, etc.
- Geometric stress concentrators include any feature which may locally increase the stress, most common material surface defects, non-metallic inclusions, or spring manufacturing induced concentrators such as tool marks.

Ideally, to validate a new design, application, material or process, the springmaker or customer will be able to perform fatigue testing which matches the expected use as closely as possible. In the case of extended life applications, this may be time or cost prohibitive, so accelerated testing at higher stress levels can be used.

Here, caution must be exercised as a higher applied stress may induce a failure mode which will not be experienced in normal usage. One example of this is high stress, creating a surface-initiated fatigue crack on a shot peened spring, when possibly under expected stresses the crack would initiate subsurface. Regardless, assuming the fatigue test mimics actual use, it is possible to design an improved process based on failure analysis results.

The goal of failure analysis is to identify the fatigue crack initiation site and the root cause of crack initiation. The complete topic of failure analysis is expansive and well beyond the scope of this article; however, in general, failure analysis uses progressively higher magnification instruments to find and study the crack initiation.

The three typical degrees of imaging include first naked eye observation, then stereo microscope analysis, and last, if needed (and available), study with a scanning electron microscope. This should be sufficient to pinpoint where the crack initiated on the fracture surface, provided there was no post failure damage. Other tools which are commonly utilized, as needed,

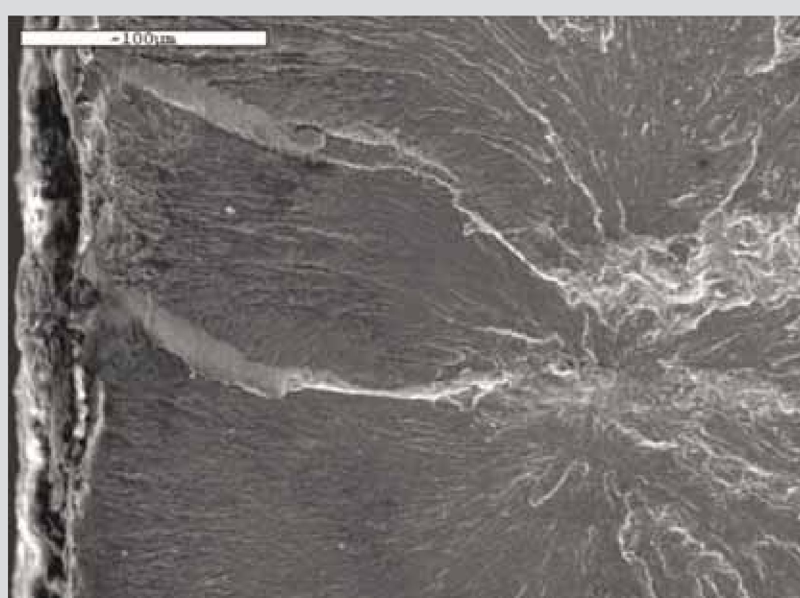


Figure 2: Scanning electron microscopy image showing the fatigue crack initiation site 225 microns below the surface. No non-metallic inclusions were present.

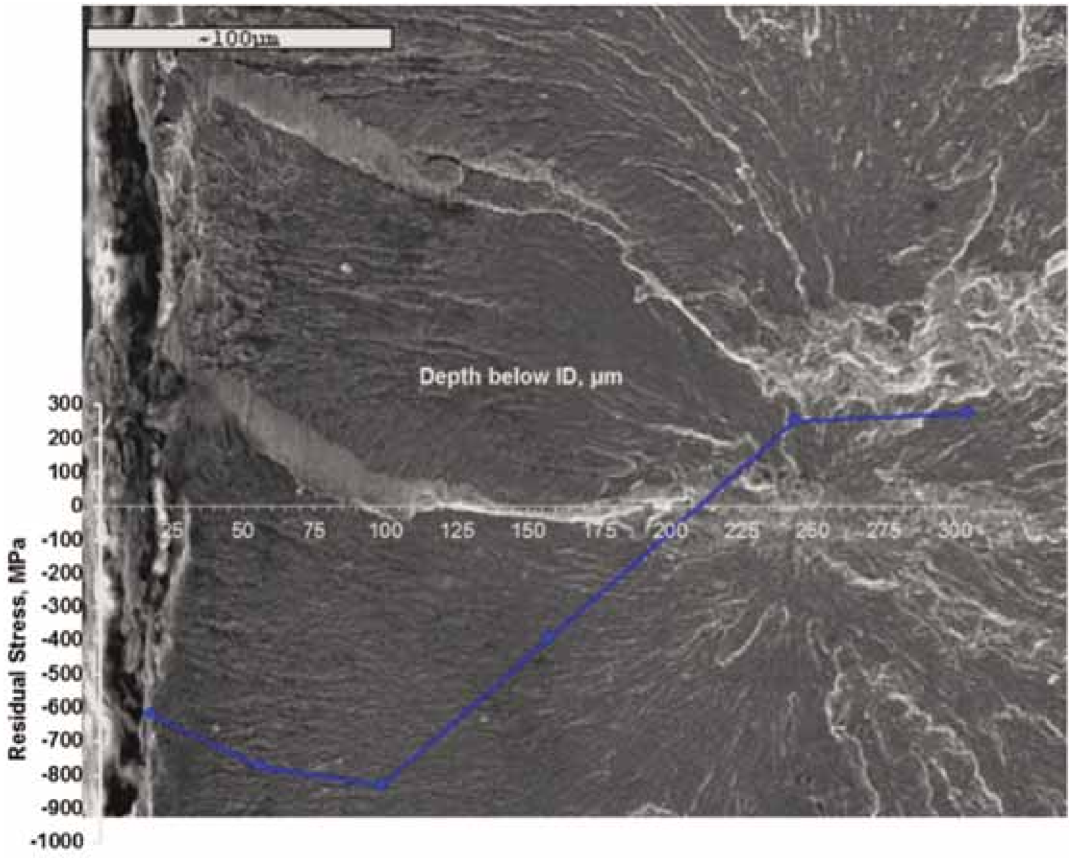


Figure 3:
Residual stress vs. depth, plotted over the SEM fractograph.

include microhardness testing, microstructural analysis, and possibly x-ray diffractometry to measure residual stresses.

Case History — Associated Spring: Engine Valve Spring

In this case, an engine valve spring was being tested on a dynamometer for a diesel marine application. The spring fractured prior to test completion and was analyzed to determine the cause of failure, guided by the four fatigue factors previously discussed. The spring fractured in one location, 3.2 coil turns from the front end. Examination using a stereo microscope indicated that the fatigue crack initiated below the spring ID, as shown in Figure 1.

Further analysis was performed using a scanning electron microscope. As can be seen in Figure 2, it was confirmed that the fatigue crack initiated approximately 225 microns below the wire surface, in the absence of any stress concentrators such as non-metallic inclusions. The material strength was verified by measuring the microhardness and was found to be about 595 HV (55 HRC). This is normal for a CrSiV alloy spring which is well processed.

The residual stress was measured using x-ray diffraction to quantify the effects of shot peening and stress relieving. The spring was found to have good compressive residual stress from peening and a normal level of tensile residual stress resulting from coiling and stress relieving. When graphically presented over the scanning electron image (Figure 3), it can be seen that the fatigue initiation depth corresponds with the depth where peening compressive residual stress disappears and only tensile residual stress remains (approx. 225 microns).

In summary, the analysis concluded that this was a normal well processed spring with no material or processing deficiencies. However, it can also be concluded that if the tensile stress at the initiation depth was reduced or eliminated, the spring would have a longer fatigue life. This provides the opportunity for process optimization.

The process optimization goal in this case is to eliminate the detrimental subsurface tensile residual stress without negatively impacting other contributors to fatigue, such as geometry, material strength, or creating any stress concentrators. Given these constraints, Associated Spring has developed several unique processes which can either eliminate that tensile residual stress or, if needed, introduce a significant compressive residual stress at that depth. Figure 4 shows the residual stress profiles resulting from these optimized processes.

The precise details of the different optimized processes will be presented in a future article. However, the point is that all were developed to eliminate the "weak link" which resulted in

Residual Stress Depth Profile

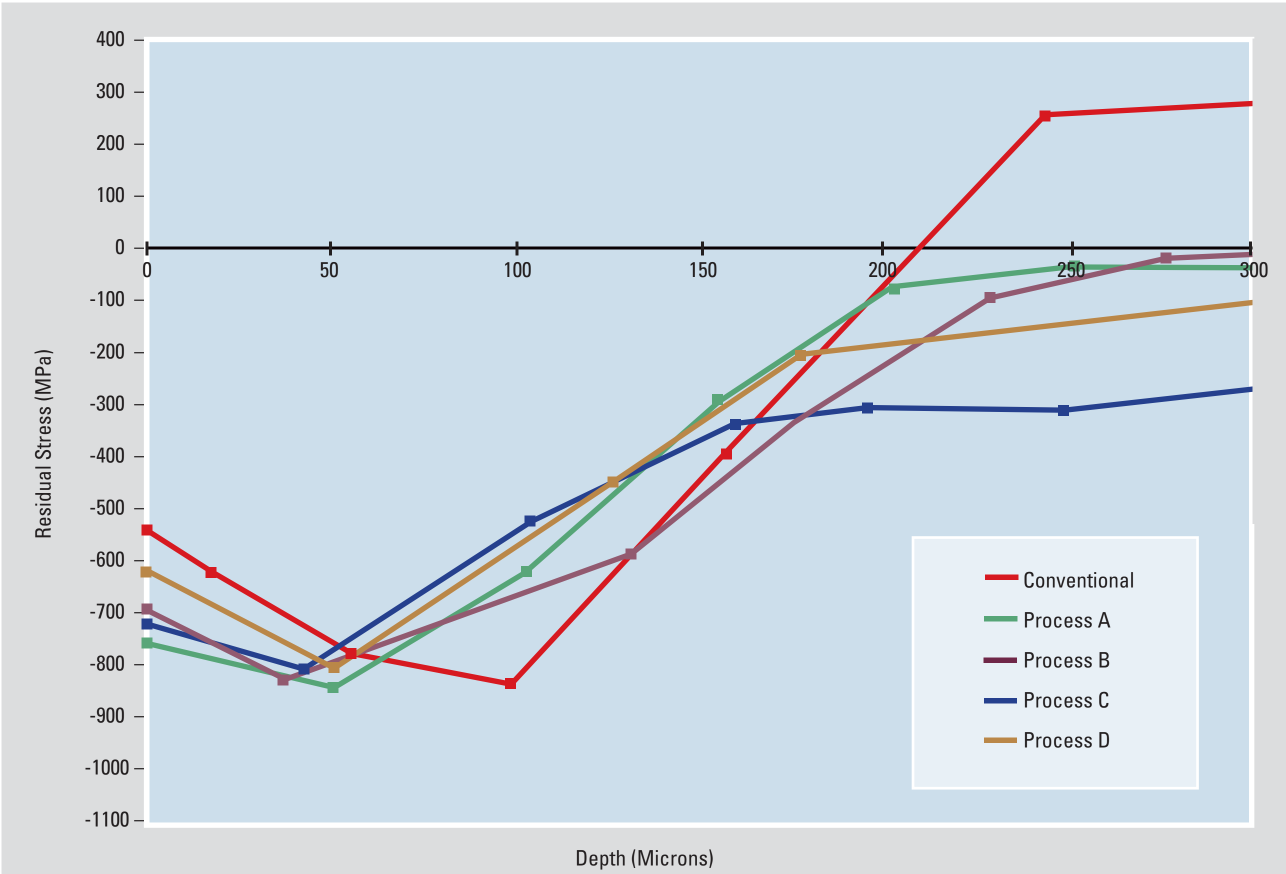
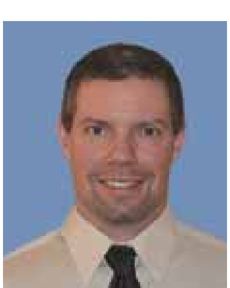


Figure 4: Residual stress vs. depth comparing a conventionally processed valve spring with 4 unique optimized processes, which eliminate the subsurface tensile stress from coiling.

premature failure in this case history. Ultimately, Process A was chosen and applied to this spring, allowing the customer to achieve the durability goal without having to change the spring design or material.

With a strong comprehension of the mechanics of fatigue life, this concept can be readily applied to any type of spring, or for that matter any product subjected to fatigue. Similar case histories exist where this has been applied to Belleville washers, torsion springs, power springs, fuel injector springs, flapper valves and others. Ultimately, the goal of process optimization is first to develop one or more technical solutions to improve fatigue life guided by the failure analysis, then decide which option is most robust and cost competitive. ■



Jason Sicotte is the new product and process engineering manager at Associated Spring while also directing the Materials Engineering laboratory. During the last 19 years in the spring industry he has gained valuable experience analyzing failures, designing new products and working closely with wire and steel mills on process improvements. Sicotte holds several patents and has formerly been a guest speaker to IVSWMA. To contact Sicotte, email: jsicotte@asbg.com.