Residual Stress – 1953 – 2018

It's 1953 and Roy Woodward is a 25-year-old engineer trying to find an explanation for the causes of fatigue cracking and how these are linked to residual stress. Components are cracking prematurely and unexpectedly with no real understanding of why.

Residual stress describes the stress locked within a component or material when all the externally applied loads and forces acting on it are removed. It can add to, or subtract from, the applied stresses and lead to unexpected consequences, such as the early failure of a part or distortion out of required tolerances – it's a common, but even today, often unidentified, side effect of many manufacturing processes.

At this time, of course, residual stress was not a common concept, not measured in the way it is today. Many engineers were aware of it but there was no contingent way of proving what the exact problem was, and within industry, as it goes in science, seeing is believing.

The next five years saw Roy testing metals and alloys to discover why these cracks were occurring. He knew that there were changes within the component that were affecting the lifespan and within this time he was able to demonstrate its effects, albeit with no measurement techniques.

Some years later, the effects of residual stress became evident again with work on military bridges. At this time Roy knew that such stresses could occur, and that rectification of shape had to be taken into account.

Over five decades later, Roy – after a lifelong engineering career in aluminium laboratories and time spent lecturing at the University of Strathclyde - read an article on work being carried out at the University's Advanced Forming Research Centre by myself and others to understand residual stress within the manufacturing industry, and drafted a letter in response.

In his letter, Roy spoke about his work throughout the years and outlined key development areas within his studies. He noted that while his findings may seem obvious to us now, it was all rather serious at the time and 20-20 foresight into such causes and effects was not available. The research that we are working on now at the AFRC was to some extent suspected by Roy all those years ago, however he couldn't prove what was happening.

Since the 1950s, residual stress has been studied, tested and measured to develop an in-depth understanding of the concept and how it can be overcome, to the point where an understanding of residual stress is now being used to improve the control of material characteristics and behaviours during manufacturing processes.

The problem Roy was dealing with in the 1950s was fatigue, a fracture mechanism within metals and alloys when they are subjected to cyclic loading and cracks begin to appear, resulting in a fracture. Residual stress plays a colossal role here, applying more force in addition to the external applied mode to cause premature failure before load capacity is reached.

The development of measurement techniques

Understanding what has happened to a component throughout its manufacture is critical. While Roy was beginning to develop knowledge within the area, and although the concept was well understood theoretically, there was still a lack of techniques and data available to determine an exact measure of any changes.

Methods for identifying, measuring and managing residual stress only started to develop during the 1970s and 1980s, providing the opportunity to begin shedding light on a previously dark area of materials science.

Within this time, two families of techniques were developed;

1. The mechanical methods in which material is removed and the stress field is disturbed. The remaining material will move to compensate for the disturbance and this can be measured to calculate how much force is required to achieve the material movement. This family of techniques is destructive and includes methods such as hole drilling and contour methods.
2. The diffraction techniques which are reliant on a source of light including x-ray, neutron and synchrotron. The metal acts like a mirror and when the x-ray hits at a certain angle, the distance between the atomic planes can be measured and residual stress can be determined.

Of course, as technology improved, so did the methods employed, including hole drilling, the contour method and more sophisticated diffraction techniques which are still evolving today.

Using residual stress to improve controlled manufacturing

In Roy's day the main focus was to create the component and the need to understand residual stress lay within preventing fatigue, but now it's possible to identify where residual stress is coming from and to establish how the evolution occurs throughout a part's manufacturing cycle. The UK is a global leader in residual stress and the AFRC is a core part of that research, developing new, industrial-scale methodologies and working with a range of equipment to measure, predict and control residual stress in real world applications, thereby making manufacturing processes more economical.

While it's tempting to assume the most important factor of manufacturing a part is to make it as strong as possible to counteract residual stresses, this is often detrimental to the material and won't solve the internal issues. To manufacture a part with decent mechanical properties, you need to have a suitable microstructure with an in-depth knowledge of how this will behave during the manufacturing process.

Throughout a typical manufacturing route, materials such as nickel-based alloys are subjected to sequential processes of forging, quenching, heat treatment, cold working and machining, while the process for the likes of steel or titanium alloys will consist of a combination of such cycles.

The heating and cooling rates throughout the process are of great importance for the development of microstructure characteristics that are required for achieving desired mechanical properties, however, the generation of residual stress throughout the manufacture is immensely problematic highly specific to the part in question.

The thermal gradients incurred during water quenching from the solution heat treatment temperature can be severe enough to generate residual stress fields of significantly high magnitudes. This is due to the rapid cooling of the outside surface causing the region to shrink and harden first, while the interior of the part is still at elevated temperatures.

As the part's hot interior cools and tries to shrink with respect to the rigid outer surface, it will go under tensile stress with a balanced compressive stress applied on the outer surface. The subsequent ageing heat treatments at lower temperatures employed for microstructure modifications might also relieve these stresses through creep deformation; however, it is rare for the stress field to be completely relaxed.

These stresses can be beneficial or detrimental to the performance of the material in service (e.g. by enhancing fatigue fracture); but, most importantly, they can influence the strategies based on which the final machining operations of the manufacturing processes are executed. This is primarily due to the redistribution of residual stresses caused by material removal, which results in the movement of the remaining material out of dimensional tolerance. By this late stage, significant value has been added, only for components to fail or distort. Therefore, understanding the generation of residual stresses during quenching and their evolution throughout the aging heat treatment becomes imperative to enhance reduced cost, right-first-time manufacturing.

Take turbine disks for example, a crucial part in jet engines. A disk with a microstructure tailored to meet its desired mechanical property can cost anywhere in the region of £100,000 to £200,000 at the final stage of manufacture – an extremely expensive part that will typically see a 60% success rate, with the remainder of material lost during a later stage of manufacture.

When a part is machined to its final required dimensional geometry, it needs to meet the exact desired tolerance - in some cases I've seen twists of five or six millimetres due to the distortions caused by residual stress - or it will fail at the point of use. Imagine a turbine disk rotating at several thousand RPM and not within the dimensional tolerance; it will create enough force to tear the entire engine apart. A quick Google search of "turbine disk failure" will demonstrate the impact of this.

If we control the manufacturing throughout the entire process, we can manage residual stress, avoid distortions and save the 40% of waste material that industry is experiencing.

Looking ahead

Technological developments and decades of research have allowed us to change the way we manufacture, building on Roy's work in the 1950s and perhaps proving what he knew but couldn't measure. However, the understanding remains in its infancy. Many aspects of microstructure evolution and microstructural design have verified residual stresses but are not understood, hence a significant portion of the work carried out by the AFRC's materials science team focuses on residual stress.

A part that has sections of varied thickness can be manufactured using forging equipment, a screw press for example, and the material's temperature elevated through heating techniques before being deformed into a final shape. Consider that there is more deformation in the thinner sections than those that are thicker, and therefore the strain rate is different in various areas of the material and the mechanical properties vary between each. It is vital to have an understanding of each property to predict the residual stress.

One of the purposes of materials testing at the AFRC is to generate accurate material models to forge a part and acquire the final intended microstructure to develop an increased understanding of residual stress.

While we continue to develop residual stress capabilities and find new ways to tackle the problem, there is still a lack of education on the subject and many SMEs are not being given the required tools to tackle the problem – an issue that Roy stressed in his letter.

There are of course barriers to businesses utilising technology, and finance is a big part of this. However, through organisations like the AFRC, SMEs have the opportunity to unlock new capabilities and save money, time and reduce the waste of material during the manufacturing of parts.

It’s now 2018 and 65 years on from Roy’s research, residual stress is still a major industry issue that cannot be ignored. As we look forward it is vital that we become more aware, within industry, academia and beyond, about one of the biggest issues faced by the manufacturing industry.