Shinning the spotlight on residual stress

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For years, residual stress was a term that many engineers were aware of, but few understood. There was a certain mysticism to the concept: residual stress was there, the effects could be seen, yet no one knew how to manage it in a practical way. That, though, began to change by the turn of the millennium. New techniques for identifying, measuring and managing residual stress – such as neutron scattering, x-ray diffraction and the contour method – were developed, shedding light on a previously dark area of science.

Perhaps one of the most famous manifestations of residual stress is Gorilla Glass®, registered trademark brand of a specialised toughened glass developed and manufactured by Coring,that was a key enabler of the iPhone. This glass achieves its toughened state through ion exchange – a process by which smaller sodium ions in the glass are replaced by larger potassium ions from a salt bath. The larger ions occupy more space and thereby create a surface layer of high residual compressive stress, giving the glass surface increased strength, ability to contain flaws and overall crack-resistance.

Similar beneficial effects can be achieved with metallic materials if the origin and nature of residual stress is understood and engineered during the manufacturing process. As an example, shot peening often introduces compressive residual stress to the surface of a component, which increases its resistance to fatigue crack initiation in service.

In simple terms, residual stress describes the stress locked within a component or material, in thermal equilibrium with its environment, when all the external 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 failure of a part or distortion out of required tolerances – it's a common side effect of many manufacturing processes.

The last few decades have seen significant advances in the technology available to detect, measure, and most importantly, simulate and control residual stress. It's now possible to identify where residual stress is coming from, and set out how the evolution occurs throughout a part's manufacturing cycle. The UK is a global leader when it comes to residual stress – 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 during various manufacturing processes.

Residual stress through the manufacturing process

Understanding what has happened to a component throughout its manufacture is critical. In a typical manufacturing route, materials may be subjected to sequential processes of forging, quenching, heat treatment, cold working and machining. This might be the process for some materials, such as Nickel-based alloys; but, for the likes of steel or titanium alloys, it is much more complicated – the manufacturing process typically consists of a combination of such cycles. This is because designing the microstructure of components with tailored mechanical properties for engineering applications requires sequential thermo-mechanical processing, often including straining and annealing at elevated temperatures, followed by rapid cooling and ageing heat treatments at lower temperatures. The heating and cooling rates are of a great importance for the development of microstructure characteristics that are the requirements for achieving the desired mechanical properties.

Achieving the right microstructure in a component that has been through so many processes and treatments requires a fundamental understanding of the material – working at the microstructural level and then engineering how it will behave when it is formed, heated, quenched, and so on. The fundamental understanding of how the material will behave allows manufacturers to start designing the manufacturing and forming processes.

For example, control of the microstructure during the manufacture of turbine discs used in jet engines – usually nickel-based superalloys - is essential to the development of the mechanical properties required for high temperature applications, typically undergoing two stages of thermo-mechanical processing;

(i) Forging and solution heat treatment at temperatures around the solvus temperature of the primary strengthening phase, followed by water or polymer quenching;

(ii) Subsequent heat treatments at lower temperatures to precipitate the secondary and tertiary strengthening phases. Heat treatments at lower temperatures partially relieve the residual stresses induced during this process, and also precipitate strengthening phases intragranularly, which are critical for high temperature creep resistance.

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.

Another illustration of the development of residual stress fields is aircraft tail frames. Typically made from aluminium 7000 series, these are forged and then quenched. However, because of their geometry, a U-shape with over three metres' span for larger aircraft, it is impossible to cool tail frames uniformly. This develops non-uniform residual stresses in the part that only manifests during the later stages of manufacturing. For such a large part, the required dimensional tolerances are less than a few millimetres. This requires the manufacturers to add additional pockets to the part to increase the stiffness of the component to prevent distortion during machining. These additional pockets, counting for almost a third of the entire part's weight, are not necessary from a structural integrity perspective, and are only considered for controlling distortions induced by residual stress. Therefore, knowing the generation and evolution of these stresses during manufacture allows engineers to modify processes to make parts, right-first-time, with reduced weight and cost.

A balancing act with material consequences

Managing residual stress is a balancing act. While it might be tempting to assume that an engineer wants to create as strong a material as possible, that is not always the case. Equally, it's not merely about making a part that's the right shape, as a lack of optimised microstructure may render it useless. Essentially, no material can possess 100% of all its required characteristics – it's a trade-off depending on the final application, which requires serious consideration of a component's manufacturing route.

When the origin of residual stress is understood, how much is in a part, and what kind of stress it is, you can then look at manufacturing methodology, make adjustments, and find new methods of optimisation. The technology and expertise exists to be more predictive with residual stress and eliminate huge amounts of waste – whether it's through redesigning a process, adding in operations, or changing machining strategies. Armed with this information and the right technology, manufacturers can simulate the machining process and remove material from specific areas or sides of the component in a way that is sympathetic to the stresses within the part.

The AFRC has developed capabilities to carry out practical and large-scale experimental trials of controlling distortions through optimised machining strategy by taking into account the generation and evolution of residual stress from the early stages of forging, heat treatment and machining. Not only are we able to predict the generation and evolution of these stresses, we can measure them accurately and use them in prediction models to simulate their effects. Without this understanding, the only way you can plan for how your component is going to move or distort when you're removing stock material, is to rely on the intuition or judgement of your more experienced manufacturing engineers and machine operators.

Measurement matters

Measurement is, therefore, a crucial issue in residual stress. Its major purpose is to use the information for optimisation and management of the residual stress to improve manufacturing processes and component design. The most popular methods of residual stress measurements, by usage, are the mechanical based techniques and diffraction-based techniques.

Diffraction techniques measure changes in the atomic interplanar spacing caused by the existence of residual stresses, and the mechanical stress measurement methods rely on tracking changes in a component's distortion through successive removal of material that results in stress relaxation.

The trickle-down effect

While the understanding of residual stress has clearly made significant progress in the past couple of decades, it remains in its infancy. What's more, in many cases, the methodologies behind some manufacturing processes remain largely analogous to where they were 50 years ago - particularly true of forming and forging processes.

This is changing. Large businesses, like Rolls Royce, Boeing, and Aubert & Duval are making significant headway in developing their residual stress capabilities and finding new ways to tackle the problem. What's still required, though, is a raising of awareness of residual stress – putting it on the technical radar of small companies and educating them about the potential strategies for tackling it.

Of course, there are questions over how to use the right technology, as well as practical and financial barriers. But, through organisations like the AFRC, we can create a trickle-down effect into the supply chain, bringing residual stress capabilities to SMEs in particular.

It may be an invisible problem in manufacturing, but residual stress cannot be ignored. With estimates suggesting the annual cost of scrapped components and waste in the hundreds of millions of pounds, it's simply too costly. It's incumbent on the entire supply chain – from industry to academia and beyond – to work together on developing new and enhanced ways of tackling one of the biggest issues facing manufacturing today.