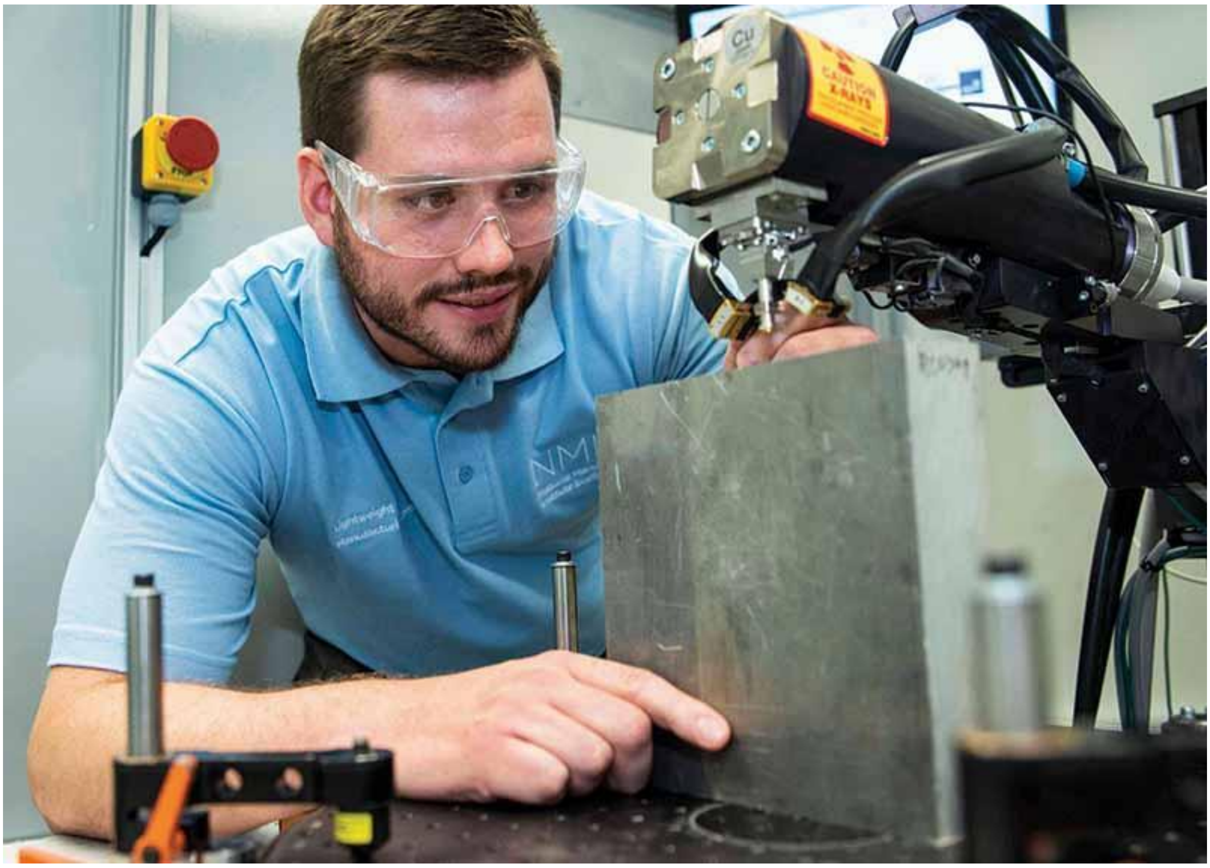
Relieving the stress - VSR for metallic parts

Dr David Easton, Stuart Laidlaw and Dr Salaheddin Rahimi FIMMM at the University of Strathclyde's Advanced Forming Research Centre, UK, seek to better understand an alternative to stress-relieving heat treatments for metallic components.



Dr David Easton with X-ray diffraction machine used to measure residual stress in a part © National Manufacturing Institute, Scotland

It is expensive, time consuming and can involve parts being transported elsewhere for weeks at a time, however, heat treatment for stress relief is a necessary evil for the manufacturing industry. Seen as essential for tackling residual stress in parts, its drawbacks are generally accepted as unavoidable.

Despite its widespread use, investigations have found that heat treatment is not always appropriate for larger components and that using it may actually lead to distortion out of required tolerances and potential scrapping of parts.

At the University of Strathclyde’s Advanced Forming Research Centre (AFRC), UK, part of the National Manufacturing Institute Scotland (NMIS), we are further investigating an alternative to heat treatment for relieving residual stress by collaborating with experts on the use of Vibratory Stress Relief (VSR).

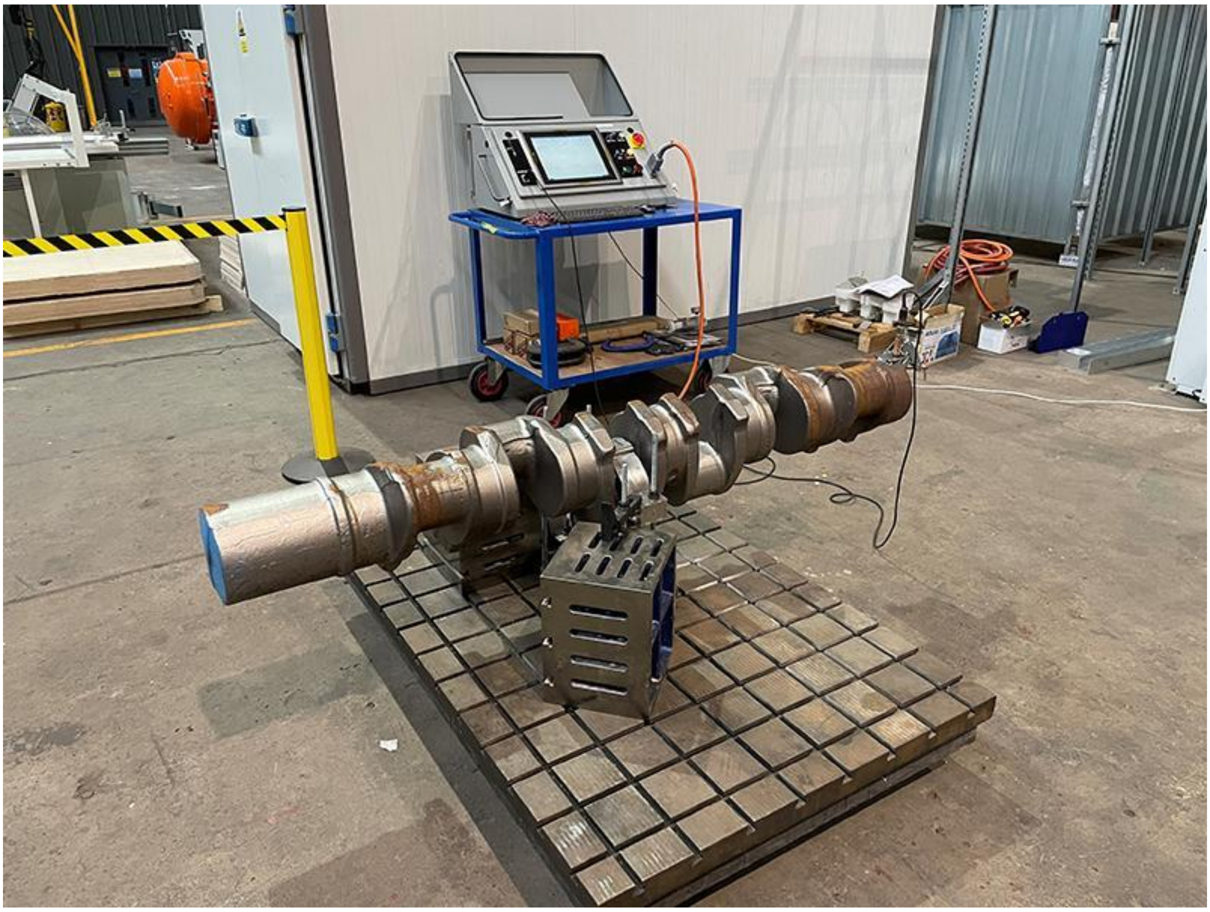
Hot topic

Residual stress is an inevitable outcome during the manufacturing processes of most high-value engineering components. These are the stresses locked within a component when all externally applied loads and forces acting on it are removed. Their generation is associated with processes and treatments that are required for achieving a tailored microstructure or material properties, which is often the determining factor.

Forming, forging and thermo-mechanical processing all create residual stress, and many metallic products will likely need heat treatment at some point throughout the manufacturing process to manage and control it.

These stresses can add to, or subtract, from the applied stresses and lead to unexpected consequences, such as the early failure of a part, or distortion at a very late stage of manufacturing, with financial consequences given the amount of money, time, material and energy that has already been put into the process.

However, while heat treatment is generally a common process when it comes to reducing such stresses, it is not without drawbacks. Heat treating parts is energy intensive, expensive, and often inconvenient as large parts need to be transported offsite for treatment. This transportation can have an undesirable impact on supply chains, causing unavoidable longer lead times and disrupting the customer and manufacturer relationship, while increasing the process’ overall carbon footprint.



VSR technology being used on a craftshank © National Manufacturing Institute, Scotland

In addition, while heat treatment remains a widely used process, it can also prove unpredictable. There is a compromise to be found in terms of the impact that traditional heat treatment has on materials – while stress is certainly reduced, it can have a similar effect on other properties such as strength and fatigue resistance. This outcome can not only be dangerous if parts are not performing to their full potential, but can waste a lot of time for manufacturers that are unable to understand the impact of heat treatment until after the part is in final stages of production.

Good vibrations

Instead of conventional methods, such as in furnaces, we clamp a vibration machine onto the part. For a stressed atomic structure, this is not dissimilar to the energy introduced through heat.

The applied energy leads to the rearrangement of the crystalline structure, resulting in stabilisation of the microstructure and stress relief without distortion.

The vibrator, with frequency band ranging from 0-100Hz, is connected to the part and supported on rubber blocks. The frequency is then gradually increased until the first resonance is reached. Two minutes is the average time required to reach this frequency. At this point, vibration is maintained for a given time, depending on the weight of the piece and its intended application. The time may range from ten minutes to an hour or more, but if it is exceeded, the piece will not suffer any damage due to fatigue or loss of tensile strength.

Based on the part’s weight, the VSR method introduces high-amplitude and low-frequency vibrations for a given period. Low-frequency vibrations carry high-amplitude energy and are very efficient in the significant decrease of peak residual stress in metallic parts and welds. The method can be used on a wide range of ferrous and non-ferrous metals, including carbon and stainless steel, cast iron, aluminium and titanium in a large variety of shapes.

Sizes vary from small welded parts, shafts and gears, to large welded and machined steel structures. However, VSR presents some limitations – it is not efficient for extruded, cold-worked and precipitation-hardened materials.

One of the most important benefits of the VSR method is its capacity to relieve stress at any point of the manufacturing process, such as after machining, snagging, drilling or grinding.

Did you know?

While a novel idea, Vibratory Stress Relief technology is certainly not new – it was first used during World War II – and its potential application has been debated for almost 80 years. However, “a general lack of understanding when it comes to underlying mechanisms and the physics of effect on residual stress, means it remains a relatively untouched technology,” say researchers at the University of Strathclyde’s Advanced Forming Research Centre.

Unlocking stress

While VSR is useful in reducing stress in a component that cannot be heat treated, for example multi-metallic structures, it can also be put to use in components where heat treatment is not practical due to time or cost.

One of the advantages is its low-cost, simple-to-use equipment. The technology is also powered from mains electricity making it less energy intensive.

Through adoption, manufacturers can gain more control over their own residual stress treatments with work carried out onsite. The machine is portable meaning long lead times and high costs associated with shipping parts elsewhere can be avoided, in addition to massively reducing the carbon footprint of transportation.

However, while evidence demonstrates that VSR technology works, it is not entirely clear how, meaning adoption remains low. At AFRC, we are working with industry to explore the observed beneficial results using fundamental scientific understanding of what happens during the processes. Additionally, we are attempting to simulate them using finite element (FE) methods.

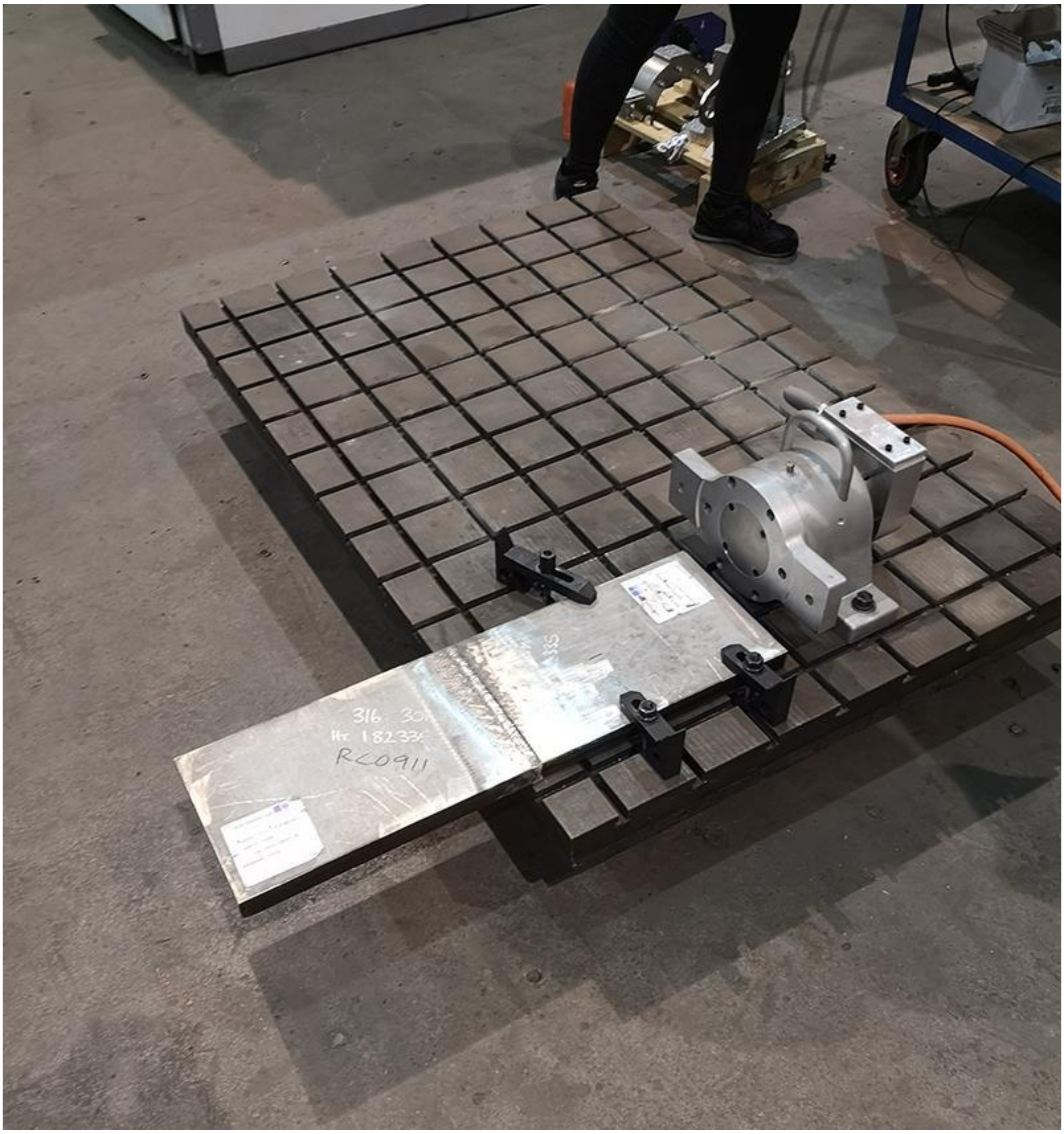
Having determined the stress state of the part at various length-scale, we carry out a VSR treatment cycle, then measure the stress state again and review changes to develop our understanding, and also to validate and enhance the results of FE prediction.

We select a sufficient number of parts at key stages of manufacturing processes and conduct stress relief using both conventional heat treatments and VSR, and measure

the magnitude and distribution of residual stresses using a combination of appropriate techniques, such as X-ray diffraction, incremental central hold-drilling and the contour method. We then compare the data with the pre-VSR and pre-heat treatment conditions to see the effects of both methods on stress evolution. Measurement is a crucial issue in residual stress. Its main purpose is to use the information for optimising and managing 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, while the mechanical stress measurement relies on tracking changes in a component’s distortion through successive removal of material that results in stress relaxation. These techniques are quite often used to complement one another to determine the residual stress profile across different scales ranging from nano to macro.

We need to demonstrate that as well as bringing benefits in stress relief, the process will not be detrimental to the part – this is important for safety-critical industries and those with a focus on lifetime performance, such as components in aircraft engines.



A generic welded part being trialled with VSR technology © National Manufacturing Institute, Scotland

Distortion and integrity

We envisage two main use cases for VSR. The first relates to residual stress itself and the way it changes structural integrity, causing issues such as creep, stress corrosion, cracking and fatigue.

For example, in the 2004 paper, *Vibratory Stress Relief in Manufacturing the Rails of a Maglev System*, published in the *Journal of Manufacturing Science and Engineering*, the authors studied VSR use in the rails of a magnetic levitation transport system. With the components being so large, heat treatment was not feasible due to the size of the furnace and the cost of treatment. Additionally, the parts must have been sprayed with aluminium coating to resist oxidation, and when heat treated at a high temperature, the coating was inevitably destroyed. Using VSR, the study found that the average principal stresses were reduced by about 30%.

The second use lies in addressing the distortion of parts. Instead of heat treatment, engineers can vibrate them to reduce potential distortion. VSR is particularly well suited to large components or structures such as ship or bridge parts, where size makes them difficult and expensive to heat treat, but very receptive to vibration. It is easier to make a large part vibrate than it is a small component. Sectors with large parts such as aerospace, marine, oil and gas, power generation, bridge construction, machine shops and fabricators could all benefit. The bigger the part – the easier the process is to run.

And while take-up in high-integrity sectors has been slow due to concerns over the lack of understanding, we are working to show the benefit that VSR technology brings.

Previous tests in marine technology have shown that VSR can in fact be highly successful in removing residual stress. The 2003 investigation, The Vibratory Stress Relief of a Marine Shafting of 35# bar steel, published in Materials Letters, found that after application of VSR technology to 35# bar steel, the macro residual stress in the component decreases notably by around 48%. However, more research is needed to see if this percentage can be further improved.

Engineers have identified essential industries in which VSR has not proven effective such as food and drink and micro-electronics – where smaller parts are used – these will continue to opt for heat treatment.

Engineers do not see VSR as a means of eliminating all adoption of heat treatment. Rather it is important that we recognise how these processes could complement one another and work together to deliver a more effective and precise end-result. For example, it is common for parts to be heat treated several times in the manufacturing process – if we can reduce the number of heat treatments and use VSR technology in their place, the savings, both financial and environmental, could be immense.