ISSN: 2277-9655
Impact Factor: 4.116
CODEN: IJESS7

IJESRT

INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

VIBRATORY RESIDUAL STRESS RELIEF IN MANUFACTURING-A REVIEW

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DOI: 10.5281/zenodo.800626

ABSTRACT
Residual stresses are stresses that remain in a solid material after the original cause of the stresses has been removed. Residual stress may be desirable or undesirable. Residual stresses remain in a body even after the removal of external forces and temperature gradients from the body. These stresses may prove to be detrimental to the service life of the body, affecting its fatigue life and dimensional stability. During the past few decades, various methods have emerged as feasible alternatives for stress relief such as shot peening, mechanical tumbling, Vibratory Stress Relief (VSR). This paper is an attempt to review VSR as a viable stress relief method, discussing its variants. Residual stresses can occur through a variety of mechanisms including inelastic (plastic) deformations, temperature gradients or structural changes .

Keyword: Residual stress, inelastic

MEASURING THE RESIDUAL STRESSES
It is important to know how large the residual stresses are in a part to predict the performance of the part. An example of the importance of knowing the residual stress in part would be if an engineer assumed the service load would not exceed 30,000 psi of tension and there is an 8,000 psi residual stress in tension in the part. This would mean that the safe service load would be reduced to 22,000 psi of tension. On the other hand, if the residual stress was in compression, the same service load would be increased to 38,000psi in tension . Residual stresses cannot be measured using the standard displacement or strain-gage measurements since these methods only measure change in stress due to applied loads. There are several different methods of measuring the residual stresses in a part including the slitting method, x-ray diffraction, holographic method, and strain-gage method.

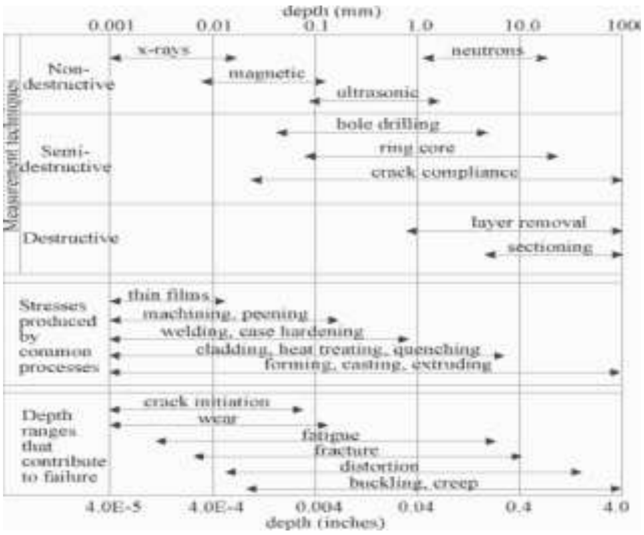

Fig:Comparison of Residual Stress Measurement Methods

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1.1 STRESS RELAXATION TECHNIQUE

The stress relaxation technique is a commonly used method for measuring the residual stress in a part. This technique is accomplished by drilling a hole into the material and measuring the surface strains that result. This can be accomplished by the Mather-Soete Drilling Technique, which places three strain gages equally spaced around a center point, as shown in Figure. A hole is the carefully drilled in the center and measurements of the changes in the stress are recorded. This method is reliable, but requires a smooth flat surface to mount the strain gages and mounting strain gages is time consuming . There are several other methods used for solid cylinders and tubes and for three dimensional solids, which follow similar procedures as the Mather-Soete Technique.

Other methods using the relaxation technique include optical and holographic methods. These methods use a laser beam to measure the displacement around the hole. The advantage of this method is that the setup time is minimal and the displacements are converted by software into the residual stresses. The displacements are compared to known states of stress.

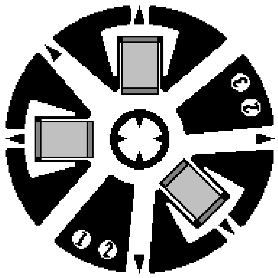
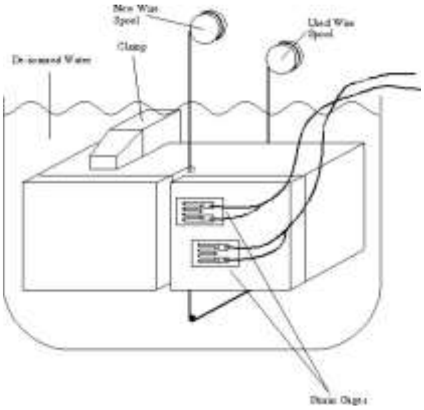


Fig: Strain Gage Arrangement for Measuring Residual Stress

1.2 SLITTING METHOD

The slitting method is similar to the relaxation method in that it cuts the material and measures the resulting displacement using strain-gages. The slit is cut by wire electric discharge machining (EDM), milling cut, or by a saw blade. The wire EDM method is preferable because it will introduce only a small amount of stress and it makes a narrow slot about 0.0035"



Wire EDM setup for Measuring Residual Stress

1.3 X-RAY DIFFRACTION

According to "x-ray diffraction is the most accurate and best developed method for quantifying residual stress due to various mechanical/thermal treatments…" The x-ray diffraction technique looks at the displacements in the atomic lattice arrangements, which are altered by stress. The measurement is taken "by measuring the angular position of diffracted x-ray beam". The change in the measurement, which is the change in the spacing of the atomic planes, is a strain that can be converted into stress, for more information and derivation of equations refer to The stress for any direction can be calculated if strain is measured in two different directions. This method is non-destructive only if the surface stresses are measured. To get the sub-surface stresses, material is ground away to expose the layer to be measured. The disadvantages of this process include being slow and this method is not very accurate for parts that have been heat-treated.

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BASICS OF STRESS RELIEF

There are two general techniques for decreasing or removing residual stresses caused by welding, which are by annealing (post-weld heat treatment) or through a mechanical treatment. There are many factors that effect the creation of the residual stresses and the stress relieving process, which include the material type, heat input, heat transfer rate, thickness of the material, type of fusion welding process, how the material is restrained, speed of the process, etc. The numerous factors in dealing with residual stress makes it difficult for an accurate prediction of stress relief process, so companies rely on their historical results or on experimental data in predicting results. The annealing or heat treatment of welded materials is the standard method for reducing residual stresses in welded materials. Weldments are slowly heated to an elevated temperature, such that temperature gradients and minimized to prevent the creation of new residual stresses. The weldment is then held at that temperature or "soaked" for a predetermined length of time .

At this elevated temperature, the yield point of the base material of the weldment is low enough for the stressed areas to plastically relax to a lower stress state. At the end of this period, the part is slowly cooled, such that new stresses are not introduced. The main problem with the heat treatment of parts is the cost in time and energy. Large weldments require an oven large enough to accommodate their size and there are only a few such ovens spread across the country. In addition, large weldments could require being "soaked" 40 hours or more to reduce the residual stresses to acceptable levels. Another heat treatment method is locally heat-treating the weld with an acetylene torch. This method will slightly reduce the residual stresses, but is time consuming and is done by hand. There are several mechanical methods to reduce or modify the residual stresses. The first method is shot peening, which involves bombarding a part with small spherical pellets.

The pellets impact the surface creating small deformations, which induce compressive stresses on the surface and tensile stresses in the sub-surface of the part. These surface compressive stresses are less likely to initiate cracking and increases resistance to fatigue failure. Cold deformation, also known as cold working, is used to stress relieve hand forgings. The part is first solution treated and quenched. Then the cold part is placed between cold flat dies and is reduced in thickness and finally the part is aged. Proof testing a weldment will also reduce the residual stresses by slightly plastically deforming the weld area, leading to a drop in residual stresses. This method is mainly used on pressure vessels and pipes.

OVERVIEW OF VIBRATORY STRESS RELIEF

Vibratory stress relief (VSR) has been used commercially for over thirty years, but only recently have scientists and engineers quantitatively and mechanically analyzed this method of stress relief. "The main purpose of VSR is to lower and redistribute stresses to safe levels such that the component's accuracy and long term stability are assured" VSR does not work for every application, as will be discussed later in this section, but it does work well for applications that do not require the change in crystal structure or mechanical properties. In addition, there are many benefits in using VSR over the heat treatment of weldments including savings in cost and time.

There are many benefits in using VSR compared to the traditional heat treatment of weldments; among them are savings in cost and time, as well as environment benefits. With VSR, the largest reduction in residual stress occurs with in the first ten cycles. This means that the VSR process will take ten minutes if the resonant or sub-harmonic methods are used, or just a few hours if the sub-resonant method is applied. In addition, the actuators used for VSR are small and transportable as seen in Figure 4.1 on the next page. Figure shows a single vibrational actuator, Meta-Lax, on a base for a dynamometer that had been milled for 80 hours after welding with a distortion of less than 0.002 in after manufacturing . Meta-Lax is a VSR process developed by Bonal Technologies, Inc., which they use for both post-weld stress relief and for conditioning during the welding process.

Vibratory stress relief can be used on any application the does not require a change in the mechanical properties or the crystal structure of a part. The VSR technique would be good for applications which require dimensional stability and applications requiring the relief of residual tensile stresses that cause early fatigue failure and stress cracking . Applications include the stress relief of tooling fixtures, welded frames, and machined parts. Figure shows some more examples of VSR applications using the Meta-Lax equipment

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FININITE ELEMENT MODEL

"The finite element method is a numerical analysis technique for obtaining approximate solutions to a variety of engineering problems" There exists an infinite number of unknowns in a problem looking at the displacement, stress, strain, or other quality. The finite element method works by simplifying the analysis. First, the shape being analyzed is divided into elements, which are connected by nodes. An interpolation function is then chosen to represent the different parameters across the element. The interpolation function is usually a polynomial, since they are easy to integrate and differentiate. The number of nodes assigned to the element dictate the degree of the polynomial. Next, matrix equations define the properties of the individual elements. The element properties are then combined to create the equations of the system. *Huebner et al* states "the basis for the assembly procedure stems from the fact that at a node, where elements are interconnected, the value of the file variable is the same for each element sharing that node" . The boundary conditions are defined for the problem and the system equations, which are comprised of a set of simultaneous equation, are solved.

In this study a finite element-modeling program, ANSYS, was chosen to create a computer model of the vibratory stress relief of pre-stressed beam. The beam was setup as a cantilever beam, with the left end connected to ground and the right end in space. A 2-D structural solid, the PLANE42 element in ANSYS, was chosen to represent the beam. The PLANE42 element is a 2-D element defined by four nodes each having two degrees of freedom, which are the translations in the x and y directions. In addition, the PLAIN42 element has the capabilities to show plasticity, creep, swelling, stress stiffening, large deflection, and large strain.

The shape of the beam was defined by three square elements connected by eight nodes, as shown below in Fig. The underformed length of the beam is fifteen inches, the height is five inches, and the depth was set as one unit deep. The depth was set as an arbitrary measurement since the frequency response section of the code requires a value.

The boundary conditions for the problem were that nodes 1 and 5 were fixed and had zero degrees of freedom. The material properties, shown in Table, were chosen to be those for the aluminum alloy 6061-T6 to compare data to several other papers, which used the same material.

Table : Material Properties of Aluminum

Density, ρ	Modulus of Elasticity, E	Poison's Ratio, ν	Yield Strength, S_y	Tensile Strength, S_{ut}
0.0975 lb/in^3	$10x10^6$ lb/in^2	0.33	$40x10^3$ lb/in^2	$45x10^3$ lb/in^2

To take in account the bilinear kinematic hardening of the aluminum as it plastically deformed, several points were taken from the stress-strain curve for aluminum 6061-T6, as shown in Figure

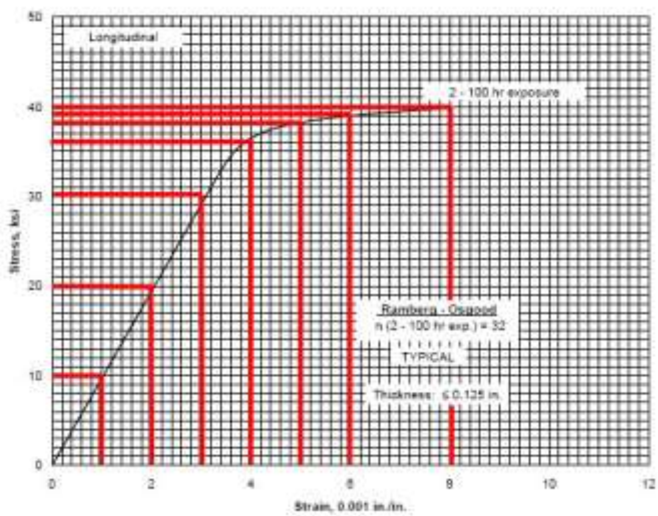

Figure : Aluminum Alloy 6061-T6 Tensile Stress-Strain Curve

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INDUSTRIAL USE OF VSR

Many present day manufacturers have eliminated thermal stress relieving on large parts either for economic and/or for performance reasons. These manufacturers span across a multitude of industries including specialized machinery, aircrafts, railcars, rolls and conveyors and mining equipments.

CONCLUSION

VSR is not used for every stress relief application. VSR technique is ideal for parts that do not require a change in material properties or crystalline structure. For these changes only a heat treatment process, such as annealing, will work. A few examples of applications that VSR is ideal for, include the stress relief of tooling fixtures, welded frames, and machined parts where dimensional stability and a longer fatigue life are the key concerns.

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Patil, M. S., Wayakole, R. R., & Sarode, K. D. (2017). VIBRATORY RESIDUAL STRESS RELIEF IN MANUFACTURING-A REVIEW. *INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY*, *6*(5), 609-613. doi:10.5281/zenodo.800626