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Modelling of Residual Stress Relaxation: A Review

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ABSTRACT

Compressive residual stress, induced by mechanical surface treatment, may relax during component operation life, due to thermal or mechanical mechanism. Fatigue life prediction for the components which have residual stress will be misled and inaccurately predicted the phenomenon of residual stress relaxation is not considered. Despite putting an effort on incorporating the residual stress relaxation, the issues remain concerned with the technical challenge of measuring and quantifying the magnitude of residual stress relaxation as well as redistribution during the loading cycling itself. In this paper, the residual stress relaxation and its models were reviewed and discussed to picture the best knowledge related to this topic, i.e. whether relaxation is a cause or an effect.

Keyword: **Residual stress, relaxation of residual stress, modelling of residual stress relaxation**

INTRODUCTION

Residual stresses are those stresses which exist along a cross-section of a component without applied external forces (Sigwart, 1957). These can be inherent in the product from the manufacturing process or induced in the finished product. Welding, machining, forming, hardening, casting and forging can lead to residual stresses in the product. Beneficial compressive residual stresses (which increase the fatigue life of the component) can be added to the component using several methods such as shot peening, laser peening, low plasticity burnishing, ultrasonic impact treatment and deep rolling.

Meanwhile, the fatigue life of metallic materials can be extended by the near-surface macroscopic compressive residual stresses (Juijerm and Altenberger 2006), as they retard fatigue crack initiation and crack growth (Niku-Lari, 1987; Altenberger, 2005; Wagner, 1999).

By using shot peening, Ali *et al*. (Aidy Ali, 2005; Aidy Ali *et al*., 2007a; Aidy Ali *et al*., 2007b; Aidy Ali and Brown, 2006) successfully improved the fatigue life of 2024-T351 Aluminium alloy aircraft friction stir welding joints. Yet again, the problem remains is the initial residual stress field inherent in or induced in the finished product may not remain stable during residual stressed component operation life. These residual stresses may decrease and redistribute, and this reduction is called relaxation. Residual stress relaxation can occur due to several reasons including thermal, static mechanical load, cyclic load and crack extension effects.

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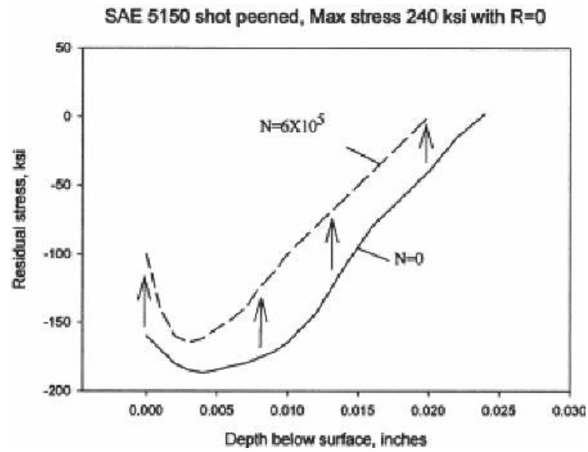

Fig. 1: Residual stress relaxation, before and after cyclic loading (10)

Many years ago, cyclic residual stress relaxation was observed by Mattson and Coleman (1954), and this is shown in *Fig. 1*. Nevertheless, the beneficial effects on fatigue life still remain because the relaxation is a partial relaxation of the compressive residual stress.

THERMAL RELAXATION

Leverant *et al*. (1979) found approximately 20% of the relaxation of the residual stresses induced by Shot Peening on Ti-6Al-4V caused by 600° F (316°C) thermal exposure alone. A primary approach for modelling the thermal stability of peening residual stresses, known as the Zener–Wert–Avrami function (V¨ohringer, 1983), has widely been used (V¨ohringer *et al*., 1984; Hoffmann *et al*., 1987; Schulze *et al*., 1993); it has a general form:

$$\frac{\sigma^{RS}(T,t)}{\sigma_0^{RS}} = \exp\left[-(At)^m\right] \tag{1}$$

Where $\sigma^{RS}(T,t)$ is the residual stress after annealing at temperature T for time t, σ_0^{RS} is residual stress value before annealing, *m* is a numerical parameter dependent on the dominant relaxation mechanism (the parameter m has been found to change with aging temperature), A is a function of material and temperature according to

$$A = C\exp\left(-Q/kT\right) \tag{2}$$

Where *C* is a velocity constant, *Q* is the activation enthalpy for the relaxation process, and *K* is the Boltzmann constant. It is used to fit an experimental data for the surface thermal residual stresses. This approach does not appear to have been extended to subsurface changes in residual stresses. Therefore, individual experimental results cannot be regarded as being entirely general, because the thermal stability of peening residual stresses is dependent on several critical peening parameters, including coverage, intensity and the resulting cold work.

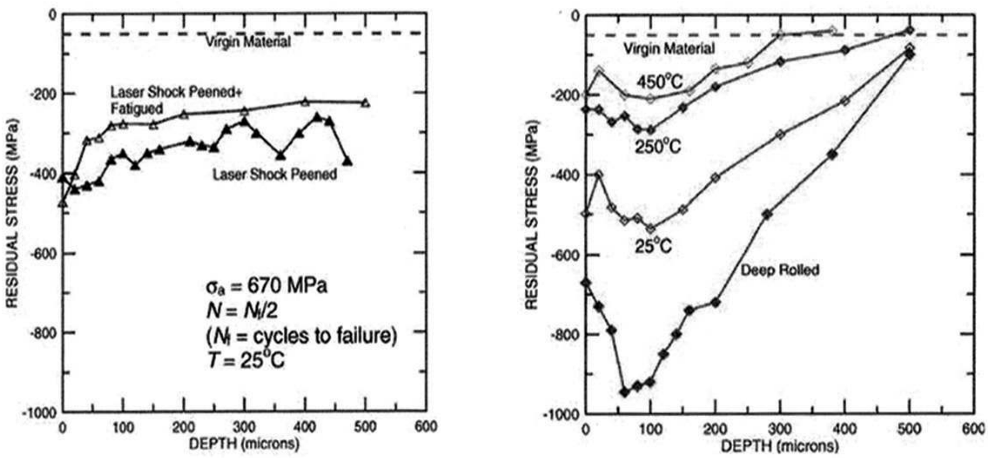

Fig. 2: Residual stress profiles, before and after fatigue cycling in Ti-6Al-4V for laser shock peening (left) and deep rolling (right) at various temperatures (17)

CYCLIC RELAXATION

If the summation of the applied stress and residual stress is more than the yield stress of the residual stress component, relaxation and redistribution of the residual stress will occur due to macroscopic plastic deformation (Han *et al*., 2002). It is worth to note that in repeated cyclic load, which is important for many mechanical components, the relaxation will also exist even when the individual mechanical load cycles do not cause deformation of macroscopic plastic.

After the first cycle in fatigue cycle for Ti-6Al-4V sheet, V¨ohringer *et al.* (1984) found a limited residual stress relaxation. For the same material, at several different temperatures for both deep rolling and laser shock peening, Nalla *et al*. (2003) showed relaxation of the residual stress profiles after fatigue cycling at load ratio of $R = -1$. As shown in *Fig. 2*, the room temperature cyclic relaxation was small for the laser shot peening and medium for deep rolling, but this was large for both processes at high temperature.

Zinn and Scholtes (1999) observed that the most relaxation changes occurred on the first cycle for the reversed bending of shot peening residual stress in several aluminium alloys (2017, 5083, 5754, 6082 and 7020), followed by a moderate relaxation (up to 30 to 40%) by the end of the fatigue life. Furthermore, a large relaxation of the compressive residual stress was found in the first fatigue cycle observed by several researchers (Taira and Murakami, 1960; Kodama, 1972; Wick *et al*., 2000; Qui and Wang, 1987), which was apparently due to the static effect, when the yield condition was less than that of the summation of residual stress and applied stress of the same sign of applied load. The followed gradual relaxation is due to true cyclic effects.

In another work by Wick *et al*. (2000), the measured surface residual stress for AISI 4140 steel after 1 cycle and after 10^4 cycles of fatigue loading at different stress amplitudes as shown in *Fig. 3*.

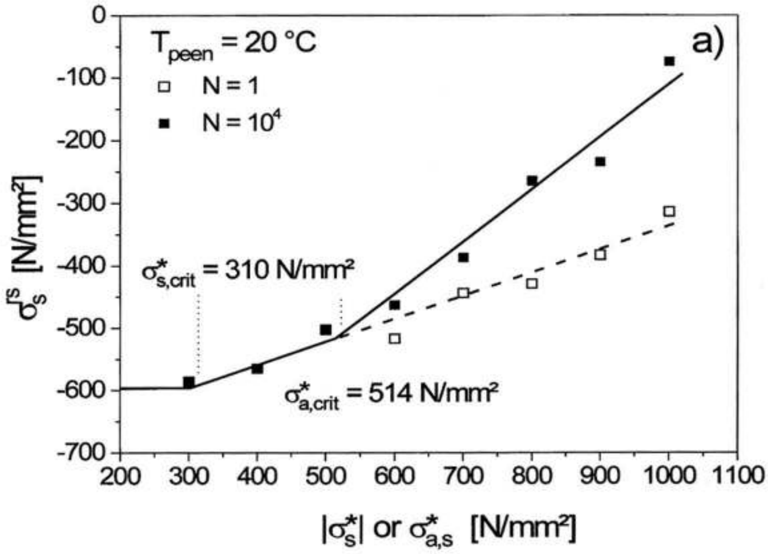

Fig. 3: Surface residual stress, as a function of fatigue stress amplitude after 1 cycle and 10^4 cycles (21)

MODELLING OF RESIDUAL STRESS RELAXATION

The benefits of surface engineering residual stresses are reduced by cyclic relaxation of compressive residual stress (Mattson and Coleman, 1954). The cyclic relaxation is affected mainly by:

(1) Initial magnitude and gradient of the residual stress field and degree of cold working,
(2) Fatigue stress amplitude, mean stress ratio and number of cycles, and
(3) Material cyclic stress-strain response and degree of cyclic work hardening/softening (Zhuang and Halford, 2001)

Morrow and Sinclair (1958) conducted strain-controlled fatigue tests to quantify the cyclic residual stress relaxation and proposed a relationship between the mean stress and the load cycle, as follows:

$$\frac{\sigma_{mN}}{\sigma_{m1}} = \frac{\sigma_y - \sigma_a}{\sigma_{m1}} - \left(\frac{\sigma_a}{\sigma_y}\right)^b \log N \tag{3}$$

Where σ_{mN} is the mean stress at the Nth cycle, and σ_{m1} is the mean stress at the first cycle. σ_a is the alternating stress amplitude, σ_y is the material yield strength, and b is a constant dependent on material softening and applied strain range $\Delta\varepsilon$. Eq. (3) is not applicable for load ratio $R \neq -1$ because the surface residual stress is only analogous to the mean stress when the material is subjected to completely reversed loading. The experimental results were only supported by Eq. (3) for $N > 10^6$ and $\sigma_{mN} < 20$ MPa.

A linear reduction in the residual stress as a function of the exponent of the number of cycles, N was proposed by Seungho Han *et al*. (2002) for welded steel components by the relationship between the ratio of the residual stress, after a single load cycle to the initial residual stress, $(\sigma_{res})_{1cycle} / (\sigma_{res})_{ini}$, and $\{(\sigma_{res})_{ini} + \sigma_{app})/\sigma_y\}$, as follows:

$$(\sigma_{res})_{relax}/(\sigma_{res})_{1cycle} = N^k \tag{4}$$

For $\{(\sigma_{res})_{ini} + \sigma_{app})/\sigma_y\}<1$

$$(\sigma_{res})_{relax} = (\sigma_{res})_{in}.N^{-0.004} \tag{5}$$

For$\{(\sigma_{res})_{ini} + \sigma_{app})/\sigma_y\}\geq 1$,

$$(\sigma_{res})_{relax} = (\sigma_{res})_{ini}.(-1.6[\{(\sigma_{res})_{ini} + \sigma_{app})/\sigma_y\}]+2.6).N^{-0.004} \tag{6}$$

They found that the residual stress relaxed by the first cycle load was large and the amount of the residual stress relaxation by the repetition of cyclic load was small enough to be neglected in an application of fatigue strength estimation.

Jhansale and Topper (1973) suggested the following relationship between the mean stress and the load cycle to quantify the cyclic residual stress relaxation:

$$\sigma_{mN} = \sigma_{ml}(N)^B \tag{7}$$

where B is the relaxation exponent dependent on the material softening and applied strain range $\Delta\varepsilon$.

Kodama (1972) measured the residual stress decrease on the surface of the shot-peened specimens using the X-ray diffraction techniques, and proposed the following linear logarithm relationship:

$$\sigma^{re}{}_N = A + m \log N \tag{8}$$

where $\sigma^{re}{}_N$ is the surface residual stress after N cycles. A and m are material constants, which are depending on the stress amplitude σ_a. It was noted that the experimental data which supported the linear logarithm decreased the relationship between residual stress and the load cycles only after the first cycle.

Using the finite element method, Zhuang and Halford (2001) proposed an analytical model for the relaxation of residual stress. The model could predict the relaxation with R=0 and R=-I very close to that obtained by the finite element method. The model incorporates the initial cold work effect. An equation for the prediction of residual stress relaxation is therefore proposed:

$$\frac{\sigma_N^{re}}{\sigma_0^{re}} = A\left(\frac{\sigma_{\max}\sigma_a}{(C_w\sigma_y)^2}\right)^m (N-1)^B - 1 \tag{9}$$

where C_w is a parameter which accounts for the degree of cold working. Material constant m is dependent on the cyclic stress and strain response, where material constant A is also dependent on the cyclic stress and strain response. Constant B controls the relaxation rate versus loading cycles. The initial residual stress is $\sigma^{re}{}_0$. To obtain the effect of loading ratio R on the relaxation, Eq. 5 can therefore be rewritten in the following form:

$$\frac{\sigma_N^{re}}{|\sigma_0^{re}|} = A\left(\frac{2\sigma_a^2}{(1-R)(C_w\sigma_y)^2}\right)^m (N-1)^B - 1 \tag{10}$$

However, an experimental study on the cycle-dependent residual stress relaxation is still required to validate the analytical and numerical models for validation.

DISCUSSION

The modelling of the residual stress relaxation by Morrow and Sinclair (1958) and Jhansale and Topper (1973) [as in equations (3) and (7)] did not incorporate the stress ratio into account because in their axial tests, the mean stresses were dictated by the initially applied mean strain which was kept constant.

As noted earlier, Kodama's (1972) experimental data supported the linear logarithmic decrease relationship between the residual stress and the load cycles only after the first cycle. Based on the data presented in *Fig. 4*, the relaxation of the compressive residual stress in the first cycle is approximately 50%. However, Kodama's model did not predict this large amount of the first cycle relaxation.

For $\{(\sigma_{res})_{ini}+\sigma_{app})/\sigma_y\}<1$, the residual stress relaxation is influenced by the micro-plastic deformation in the micro-structural levels. This microstructure mechanism did not take into account in the Seungho Han's model.

Reducing the load amplitude in Zhuang and Halford (2001) analytical models will cause the relaxation to slow down. The model can be used to predict the residual stress relaxation trends, but it requires validation by an experimental study on the cycle-dependent residual stress relaxation.

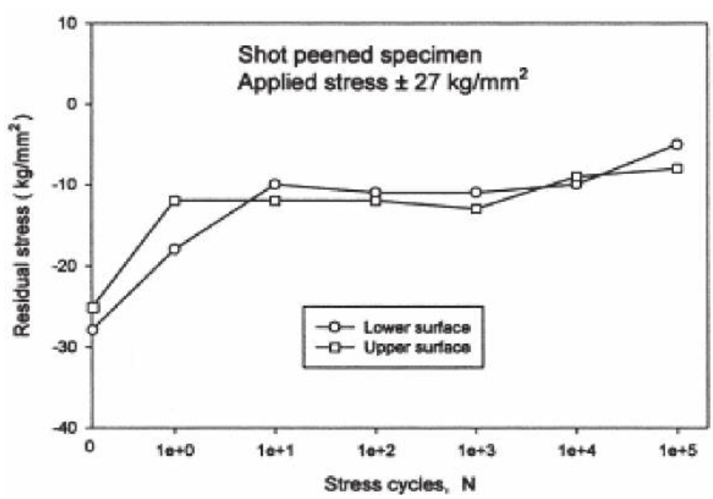

Fig. 4: Residual stress relaxation at the surface of a specimen (20)

CONCLUSIONS

In this review, it appeared that the residual stresses relaxed during the operation life of the component and this relaxation reduced the benefits of the compressive residual stresses. Despite the relaxation of the residual stresses, there are still benefits from the remaining residual stresses. There are no definitive explanations or models for all the relaxation phenomena for the cyclic relaxation. As a general observation, the large amount of relaxation occurred in the first few cycles. This was particularly due to static for the load with the same direction as the residual stress direction. After the static relaxation, it then went to gradual cyclic relaxation. The numerical model proposed for the cyclic relaxation requires some further detailed study to evaluate its practicality. Experimental models are useful to characterize cyclic relaxation. Accordingly for an accurate life modelling, characterizing and employing a correct residual stress field is important.

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