Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials Design and Applications
http://pil.sagepub.com/

A theoretical review of the operation of vibratory stress relief with particular reference to the stabilization of large-scale fabrications

C Walker

Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials Design and Applications 2011 225: 195 originally published online 13 June 2011
DOI: 10.1177/0954420711402877

A theoretical review of the operation of vibratory stress relief with particular reference to the stabilization of large-scale fabrications

C Walker

Department of Mechanical Engineering, University of Strathclyde, Glasgow G1 1XJ, UK. email: colin.walker@strath.ac.uk

The manuscript was received on 10 January 2010 and was accepted after revision for publication on 15 February 2011.

DOI: 10.1177/0954420711402877

Abstract: Vibratory stress relief (VSR) is widely used on large welded fabrications to stabilize the structures so that they do not distort during further machining or during operational duty. The level of applied stress achieved during VSR on such structures is only 5–10 per cent of the yield stress. It is, therefore, not obvious how these applied loads come to modify the level of residual stress. It is suggested here that the reason for the success of VSR applied to large fabrications lies (a) in the origin of the residual stresses and (b) in the partial relief of these residual stresses by the initiation of the transformation of retained austenite particles (in the size range from 1 to 25 μm) by the movement of dislocations into positions that are favourable for the nucleation of martensite embryos. The shear deformation associated with the transformation of retained austenite into martensite will reduce the residual stress field to the point where the stability of the structure may be assured.

Keywords: vibratory stress relief, retained austenite, phase transformations, residual stress, constraint

1 INTRODUCTION

All structures contain residual stresses. These may interact with service loads to distort or crack the structure. Accordingly, the control of residual stresses is a matter for concern. In the main, the control of residual stresses is accomplished by careful design, choice of materials, and thermal stress relief. Since it was first reported in 1943 [**1**], the use of vibration to modify residual stresses (vibratory stress relief – VSR) has been repeatedly proposed as an alternative to thermal stress relief, and is widely used to this day. In general, VSR is applied to a structure by means of an out-of-balance weight driven by an electric motor. This is clamped to the structure and the frequency of the motor is increased until a resonance is reached. The structure will be supported on rubber pads placed at points where the nodes in the vibration pattern will occur. The process is monitored by noting the reduction in the resonant frequency of the structure and is held to be complete when the resonant frequency is stable.

While there is an ample body of work relating to the satisfactory operation of VSR as a means of stabilizing fabrications, research studies set up to investigate VSR have not progressed greatly since Dawson and Moffat [**2**] indicated their belief in 1980 that ‘the various research investigations, aimed at assessing and explaining the process, have arrived at a variety of conclusions ranging from open scepticism to guarded optimism.’

The range of materials that have been studied include low-carbon and alloy steels and aluminium alloys, while the structures range from small laboratory specimens to castings and fabrications weighing many tonnes [**3**–**6**].

What is remarkable about almost all these papers is the treatment of the materials as a free variable – in essence, the details of the material have been regarded as of passing importance – and this has contributed greatly to the diversity of the outcomes, since even materials which are of the same nominal chemical composition may have quite different thermomechanical processing histories, and in consequence, the grain size and phase composition may be different.

Nevertheless, it must be said that VSR has had success in applications where it would be difficult to achieve the same ends with thermal heat treatment. Recently, the welded rails for the Maglev high-speed train, built to enable rapid access from Shanghai to its airport, have been fabricated and given a VSR treatment to ensure that they will remain flat and stable for the working life of the railway [**7**]. The relevant residual stresses were reduced by up to 40 per cent in the fine-grained, normalized low-carbon steel (StE355). In this application, VSR may be said to have been entirely satisfactory. The use of thermal stress relief was not considered desirable, as the rails were given a spray coating of aluminium to resist corrosion, and also the size of the rail sections at 3 m of length was larger than the available annealing facilities.

On the other hand, a careful study by a Dutch–German group which set out to evaluate the potential for VSR to (a) reduce residual stresses and (b) measure how this affected the subsequent fatigue life of the components, came to the conclusion [**8**] that VSR was not at all effective in prolonging the fatigue life of the welded T-joints that were the subject of the investigation. The material concerned – steel alloy StE 690 – was chosen as having a high yield strength (774 MPa) in order to obtain high levels of residual stress in the welded components. In this case, the thermal stress relief process was more successful in controlling the residual stresses. A comment was made by the suppliers of the vibration equipment that the specimens – at 50 kg – were at the lower end of the size range that were suitable for treatment by VSR.

These two examples show the diversity of outcome expected of the technique – first, it was stability that was the aim; second, it was an extension of fatigue life.

2 THEORY OF THE OPERATION OF VSR

In its simplest form, VSR may be understood by referring to Fig. 1, in which a beam is considered. Initially, the outer layer on each side of the beam is presumed to be in a state of residual tension, parallel to the length, equivalent to the yield stress in the material; as the beam is bent, the outer layer on the outside of the curve follows a load path that takes it along the plastic section of the stress–strain curve. As the beam is released, the outer layer will be unloaded elastically, so that when the beam is straight, the outer layer is in a state of zero stress. The top of the beam

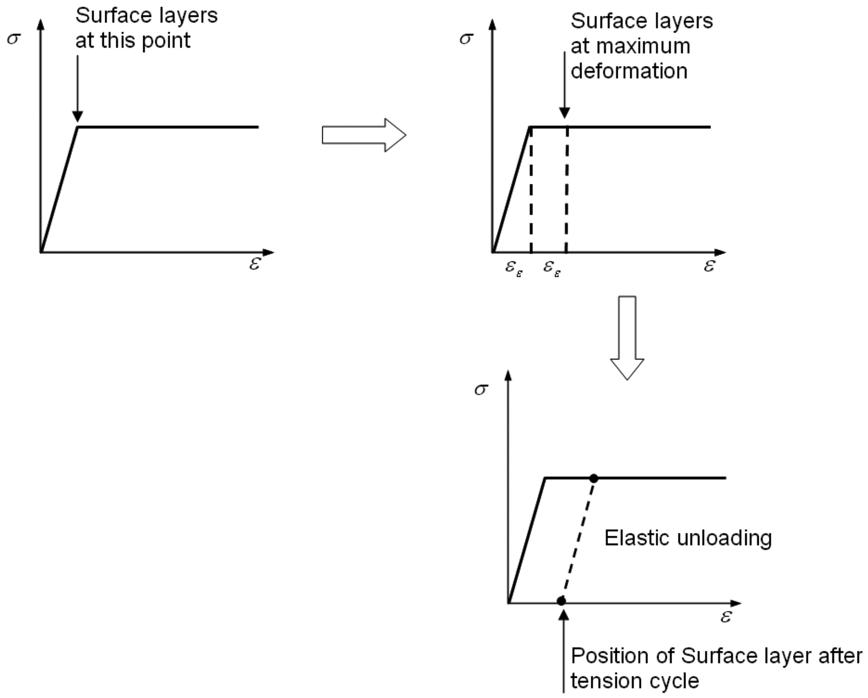


Fig. 1 Mechanism of stress relief in the plasticity model of VSR

has been stress-relieved, since if the bending is repeated, the top element will simply load and unload elastically.

The element on the inside of the curve, on the other hand, will be unaffected by the compressive loading – it will unload elastically. However, if the bending is reversed, it will now be on the outside of the curve, and follow the same strain path of plastic yielding followed by unloading.

Thus far, it would appear that in real materials, rather than the artificial situation envisaged above, a few cycles of vibration should decidedly reduce the levels of residual stress in a component, even if the state of stress is more complex than that considered here. In essence, the residual stresses and the vibration-induced loads have combined to cause local yielding that has reduced the global state of stress. This has been named the plasticity model for the operation of VSR. A similar conclusion was reached by Dawson and Moffat [**2**] who also showed that there was a threshold stress below which no effect was observed, reaching a situation where at an applied cyclic load of 0.85 of the 0.2 per cent yield stress, one could completely relieve a residual stress of 0.4 of the 0.2 per cent yield stress. The method they used to induce the residual stresses – reverse bending – did not allow them to evaluate a residual stress level higher than 0.4 of the 0.2 per cent yield.

The existence of a threshold effect was also confirmed [**9**] by a study of residual stress in mild steel induced by a precisely controlled rolling process. This gave a residual stress profile similar to that postulated in Fig. 1, with a thin surface layer close to the material yield point, and the body of the specimen under a low level of residual compressive stress. At levels of applied stress below 50 per cent of the yield, there was no evidence of a VSR effect, even after 10 000 cycles of applied loading. Higher levels of applied vibrating stress were effective in reducing the levels of residual stress in these specimens (Fig. 2).

If these two studies of small-scale specimens are summarized, it may be seen that the plasticity model of the operation of VSR is basically confirmed, with the caveat that a substantial threshold effect does exist.

However, if the experience obtained with larger specimens is reviewed, it is found that the plasticity model no longer has the power to explain the observed behaviour.

As an example, the stress levels applied to the 18-m long beam described in Adams *et al.* [**3**] (Fig. 3) may be evaluated.

From the acceleration measured at the extreme end of the beam, it may be calculated that the maximum stress induced at the midspan was no greater than 10 per cent of the yield stress in the material (mild steel AISI 1018 – yield stress, 300 MPa). This is well

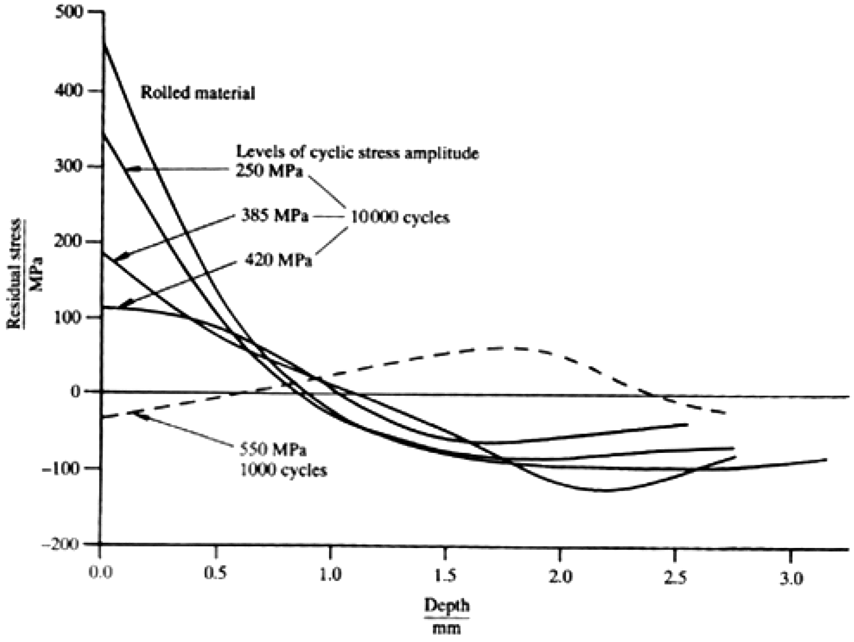


Fig. 2 The effect of vibration on residual stress induced by rolling (1 per cent reduction) in a sample of mild steel
Note that there is no effect till the induced stress reaches 250 MPa

below the threshold measured on the smaller specimens, and if the same conditions were to apply, there should have been no VSR effect observed. In fact, the VSR was successful in stabilizing the whole central section of the beam against distortion despite further radical machining processes – the removal of more than 1000 kg of material. This experience has been replicated in other applications, including a large turbine generator retainer ring (Fig. 4). Further examples may be found in Mordfin [**4**].

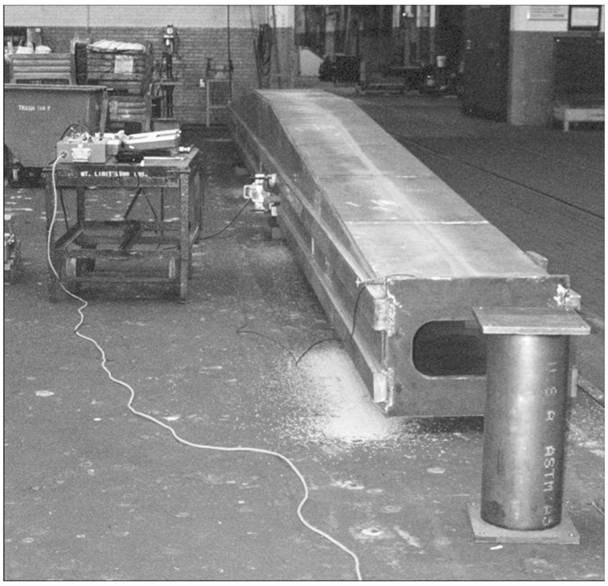


Fig. 3 Milling machine gantry (length 18 m) set-up for VSR treatment. The vibrator unit is clamped to the beam adjacent to the instrument stand. An accelerometer is fixed to the top end of the beam. Photograph by courtesy of the VSR Group of Airmatic Inc

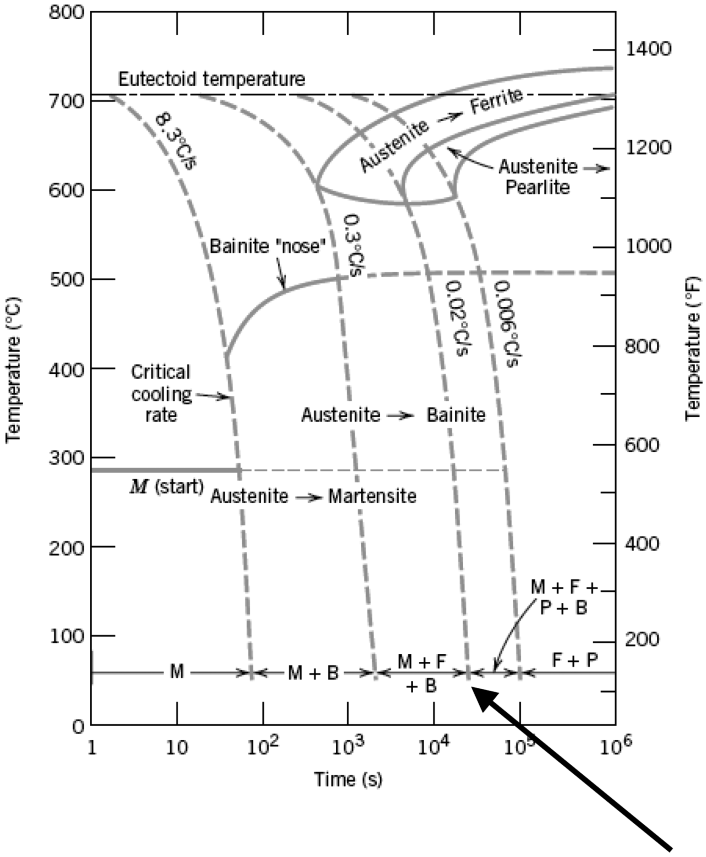
One may conclude that there is a difference between the way that VSR operates in small, laboratory-scale specimens, and the multitonne components where it has been found to be a viable and successful process. It is the central hypothesis of this article that the difference lies in the way that the residual stresses are generated in the two cases.

3 ORIGINS OF RESIDUAL STRESS IN FERROUS ALLOYS

If the small-scale specimens used by Dawson and Moffat [**2**] and Walker *et al.* [**9**] are considered, these both derive from cold plastic deformation – from reverse bending in the case of Dawson and Moffat, and from rolling in the case of Walker *et al.* The residual stresses arise from the intense shearing of the material, with consequent dislocation entanglements and grain deformation.

The origins of the residual stresses in welded components is quite different in that they arise from differential thermal contraction and the progress of the phase transformations during the cooling of the material after welding (Fig. 5). During the later stages of cooling, the levels of residual stress rise rapidly due to the thermal contraction of ferrite, which has a large coefficient of thermal expansion, and a high yield stress [**10**, **11**] (Fig. 6).

Fig. 4 Hydropower wicket gate bearing ring during VSR treatment. Material – cast steel, with welded repair. The ring has an internal diameter of 5.6 m. Approximate weight is 40 tonnes. Photograph courtesy of the VSR Group of Airmatic Inc



Approximate rate of cooling
for a large casting (ref 11)

Fig. 5 CCT diagram for a typical low-carbon steel

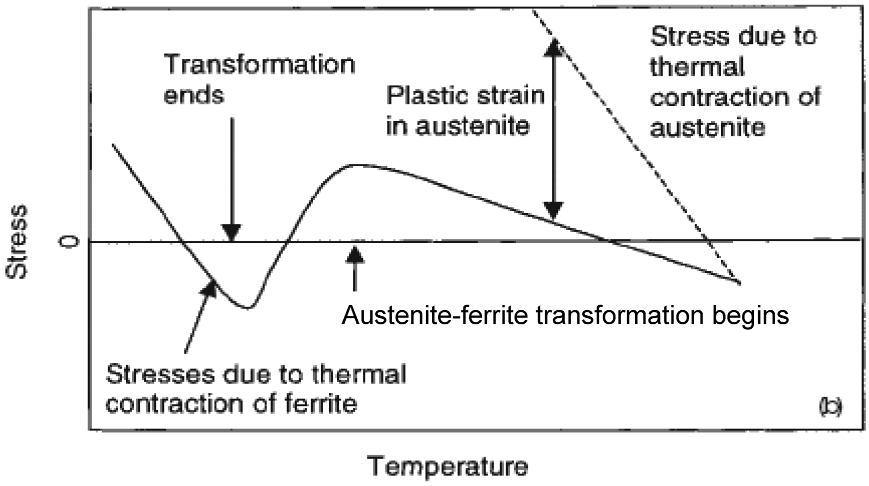


Fig. 6 The development of residual stresses by the differential expansion of phases during cooling (after Bhadeshia [**10**])

Due to the mass of the component, the rate of cooling is slower in larger specimens than in small-scale specimens, especially if they have been preheated to minimize the thermal shrinkage stresses, giving ample time for the low-temperature equilibrium phases to develop, and for the residual stresses to arise by these mechanisms. As an example of the timescale in large components – in this case a turbine rotor – Shi *et al.* [**12**] found a cooling time of 3.5 h from 840 °C to 100 °C, whereas a prismatic bar of dimensions 55 mm × 10 mm × 10 mm cooled through the same range of temperature in 30 s [**13**].

In fact, this mechanism, whereby the final level of residual stress may be largely derived from the phase transformations, explains why some fabrications resist post-weld heat treatment to reduce the residual stresses – since the stresses arise from the cooling process itself, further heating and cooling will not necessarily reduce the room temperature residual stresses.

3.1 Effect of constraint on the residual stresses

In large components, it is to be anticipated that the degree of constraint will be high, since the cooler outer layers will exert a compression on the still-hot inner layers of the structure. The dependence of the residual stress state on the state of constraint has been evaluated for a TRIP steel by Berrahmoune *et al.* [**14**] in a study that showed that the retained austenite could end up in a state of stress ranging from 275 MPa in tension to 75 MPa in compression before being strained**.**

The detailed operation of these mechanisms will depend upon the actual alloy composition, and upon the geometry of the component. In a study of small-scale welded specimens, Munsi *et al.* [**15**, **16**] measured the effect of VSR on low-carbon steel specimens 3 mm thick and 20 mm wide, with a weld bead laid down on one side of the specimen at midspan. The residual stresses were measured by X-ray diffraction and were found to be insensitive to the applied vibration at stress levels below the yield stress in the base material. In these specimens, the rate of cooling was such that the austenite was not stabilized by the combination of carbon diffusion and the subdivision of the austenite grains, (see section 6 for a discussion of this effect) and so the low-stress mechanism could not operate. VSR was only effective in reducing the residual stresses according to the plasticity model – i.e. after the application of vibratory stresses that were a large fraction (70–100 per cent) of the local yield stress.

4 REACTION OF THE RESIDUAL STRESS PATTERNS TO APPLIED VIBRATION

4.1 Cold-deformation-induced residual stress

The two sets of specimens can now be differentiated by the way in which their residual stresses were induced. The specimens that were cold-deformed were unaffected by applied vibration until the local applied stress exceeded the local yield strength of the material. A threshold effect was observed, and the application of stresses that were a large fraction of the yield stress was required for the residual stress regime to be altered.

4.2 Residual stress in large welded components

By contrast, in larger components where the residual stresses have arisen as a result of the slow cooling from the welded state, and the consequent differential phase contraction, the residual stresses were reduced by low levels of applied stress – in the range 2–10 per cent of the yield stress in the material. In this case, the definition of ‘large’ will depend upon the alloy, the detailed weld design, and the mechanical constraints that result from the geometry of the component.

5 RESIDUAL STRESS REDUCTION IN LARGE COMPONENTS – REVISED THEORY

A situation is now reached where consideration may be given to the mechanism whereby VSR reduces the residual stress levels in the large components as described in section 1. It is possible to rule out a thermally activated process since the rate of diffusion at room temperature is very low [**17**, **18**]. Bulk plastic flow, as observed in the specimens where the stress was induced by cold plastic work, may also be ruled out on the grounds that the applied stress levels are too low by a factor of 5–10.

It is proposed here that the mechanism depends upon the vibration creating nucleation sites for the transformation of retained austenite to martensite. When the austenite transforms, it does so by a shear mechanism that involves large strains, which in turn can act to reduce the residual stress field. Since no diffusion is involved, the transformation, once initiated, goes to completion almost instantly (the transformation front moves at the speed of sound). The details of the mechanism for the transformation are well known, and have been reviewed in depth [**17**, **18**].

It may be shown that for a plate of martensite to grow, there must first exist a nucleus in the form of a coherent martensite embryo in the austenite grain. It has been shown that for such a nucleus to grow, it must be at least 20 nm in diameter and ~0.5 nm thick [**17**]. The energy required to create such a nucleus in the austenite is ~20 eV, which is much too high to arise from random thermal fluctuations. It was suggested by Olson and Cohen [**19**] that the necessary energy may be derived from a distortion of the matrix by the cores of dislocations, and more recently, it has been shown by modelling that arrays of dislocations may be brought into alignment such that they will create favourable conditions for martensite embryos to form [**20**] (Fig. 7).

5.1 Dislocation mobility

VSR is normally controlled by monitoring the fall in the resonant frequency of the structure that is being used for excitation. This fall is related to the mobilization of dislocations within the structure and the associated fall in the stiffness modulus, and is not related to the phase changes [**9**]. The VSR treatment is terminated when the resonant frequency is stable – i.e. the process of mobilization of the dislocations has reached a limit. From a practical standpoint, this is both convenient and logical – there is little to be gained from further prolongation of the treatment. In fact, Walker *et al.* [**9**] showed that the resonant frequency shift reached a plateau after 10 000 cycles and remained stable for a further 250 000 cycles. This experimental experience shows that even low levels of applied alternating stress can mobilize dislocations in the manner required for them to create martensite nuclei.

5.2 Martensitic reaction

Briefly, then, the austenite–martensite transformation proceeds when (a) a nucleus approximately 20 nm in diameter is present to allow the formation of a martensite embryo and (b) retained austenite which can transform is present, since austenite may be in a state of stability that ranges across the spectrum from large grains that will transform readily (Fig. 8) to submicron grains which will not transform at all owing to the large surface strain energy that begins to be significant at grain sizes below 0.1 μm (Fig. 9, [**21**]). If it is postulated that the VSR operates to create nuclei by moving dislocations into the correct configurations it may be understood, how the process of VSR proceeds over many cycles of vibration, as there is an element of chance as to just when dislocation interactions will generate the correct condition at each nucleus site – i.e. all the retained austenite grains are not going to transform on the first cycle of applied stress.

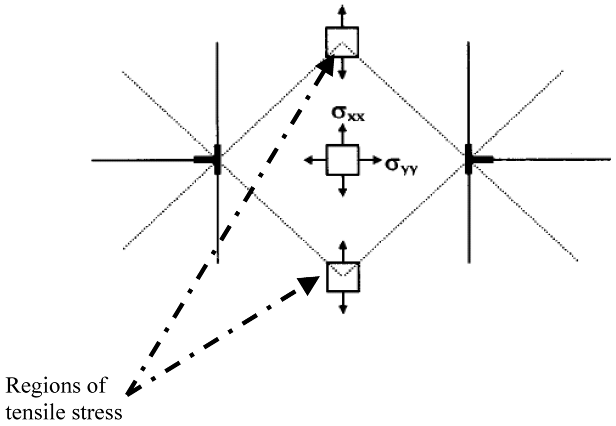
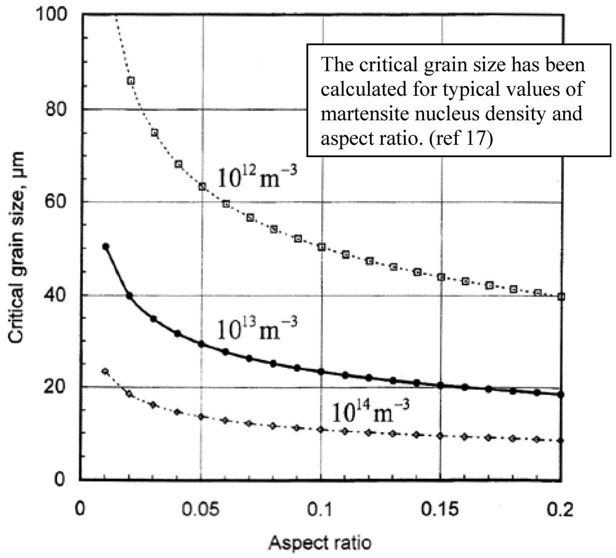


Fig. 7 The interaction of the two dislocations creates regions of tensile stress which are favourable for the creation of martensite embryos [**18**]



The critical grain size has been calculated for typical values of martensite nucleus density and aspect ratio. (ref 17)

Fig. 8 Stabilization of austenite during cooling – critical grain size as a function of aspect ratio and martensite nucleus density

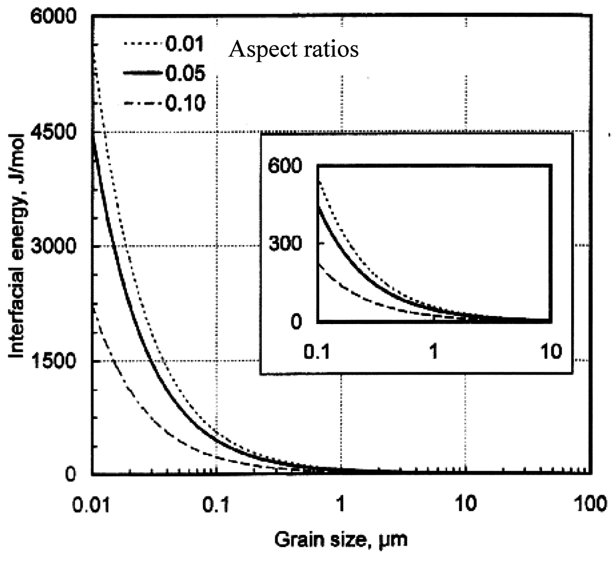


Fig. 9 Stabilization of austenite during cooling – interfacial energy of the transform surface as a function of grain size in a 1.6 per cent carbon steel [**17**]

For this to be accepted as a viable explanation of the observations in large structures, there are a number of points that need to be addressed as follows: (a) what evidence is there that there will be retained austenite at room temperature, despite the fact that this phase should transform well above room temperature and (b) how does vibration interact with the material to enable the austenite to transform in the absence of other driving forces?

6 STABILIZATION MECHANISMS OF RETAINED AUSTENITE

From an examination of the continuous cooling transformation (CCT) diagram for a typical low-carbon steel (Fig. 5), one may see that the high temperature phase austenite should transform completely at temperatures well above ambient, even if the material is quenched. At rates of cooling found in large structures, the room temperature structure may be evaluated from the CCT curve, where it may be seen that the equilibrium structure will be a mixture of martensite, pearlite, ferrite, and bainite.

There are, however, several mechanisms that serve to stabilize the austenite so that it may be retained at ambient temperatures [**21**]. This topic has been discussed in detail by Wang and van der Zwaag [**21**] with particular reference to the behaviour of TRIP steels. For the alloys commonly used for large-scale fabrications (basically low-carbon steels), the principal stabilizing mechanism is the subdivision of the austenite grains into smaller and smaller units by the products of transformation, till at grain sizes below about 25 μm, when the austenite grains cannot transform as they no longer contain nuclei for the martensite embryos (Fig. 8). This is a geometric effect, which was first observed by Turnbull and Vonnegut [**22**] in 1954, and has more recently been investigated by Bai *et al.* [**23**]. The density of martensite embrionic sites may be calculated [**21**], once the grain size reaches a diameter of 25 μm; there are no longer enough embryonic sites for each grain to contain at least one, and the reaction ceases.

If further transformation is to take place in the small grains which are without nuclei, more nuclei need to be generated, since the energy barrier for nucleation is well above that which may arise from thermal fluctuations [**17**].

6.1 Carbon diffusion during cooling

Also, the slower rate of cooling in the larger structures allows time for carbon to diffuse out of the ferrite into the austenite. Higher carbon levels in the austenite grains act to inhibit transformation [**21**] by lowering the temperature at which austenite will transform spontaneously to martensite [**14**].

6.2 Stress reduction during transformation

As each grain of austenite transforms, the energy released equilibrates with the energy stored in the surrounding crystal grains to reduce the local stress field. Since the energy released by the transformation is 1–2 orders of magnitude greater than the elastic energy stored in the material at yield, the transformation of a small proportion of retained austenite will relieve the stresses in a large volume of steel. This effect has been modelled by Ferguson *et al.* [**13**], using the *Dante* simulation package, to the effect that the martensite transformation may generate a stress of 400 MPa during the quenching and tempering of a prismatic bar of Pyrowear 53 steel alloy.

These stabilization mechanisms have been investigated by Bai *et al.* [**23**] in a study where they cooled a Nb-microalloyed TRIP steel at two different cooling rates from a 400 °C holding temperature. The slower cooling rate (2 °C/s) resulted in retained austenite grains mostly larger than 2 μm, while the faster cooling rate (10 °C/s) resulted in a retained austenite grain size below 1 μm. The larger grains were relatively unstable, in that they transformed at low levels of applied strain, and so did not contribute to the TRIP effect as desired in that material. From the VSR viewpoint, it is the larger retained austenite grains which will transform, given the creation of a martensite embryo. The small grains are inhibited from transforming by the increasing relative importance of the surface energy as the size decreases [**21**]. The stability of small grains of retained austenite has been confirmed by Jimenez-Melero *et al.* [**24**]. They performed X-ray diffraction studies on a TRIP steel during cooling and were able to follow the transformation of individual grains. Their work confirmed the hypothesis that size effect and carbon concentration work together to stabilize the austenite grains.

Modelling of welds [**25**, **26**] and of the interaction between diffusive and displacive transformations [**27**, **28**] have shown that the development of the phase structure that arises does so as a result of a dynamic interaction between composition and thermal history that may not be evident from a consideration of the CCT curves alone (Fig. 5).

In particular, Becker *et al.* [**26**] have shown how the residual stress pattern in a multipass weld may be resistant to post-weld heat treatment, contrary to the presumption that annealing will largely eliminate residual stresses.

Bouville and Ahluwalia [**27**] have shown using Ginsburg–Landau theory how the phase transformations in a model system are a matter of ongoing evolution owing to the interaction between the transformations that depend upon diffusion, and those that do not (the displacive transformations – e.g. the martensite reaction), and that the observed mechanisms for the retention of austenite may be predicted from the thermomechanics of the lattice.

It may be concluded from these strands that the state of phase composition in large specimens is radically different from those in small specimens, even when they have nominally been prepared by the same welding process, and that there will be quantities of retained austenite as a finely divided set of grains.

7 APPLICATION TO VSR

A revised theory for the operation of VSR was introduced earlier. The evidence for the necessary conditions for this theory to operate has been reviewed. The functioning of VSR will now be discussed in more detail.

It should be recalled first that all metals contain distributions of dislocations. Under the alternating stress field of the VSR process, these will be mobile, and will rearrange themselves within each grain and subgrain. It was first suggested by Olson and Cohen [**19**] in 1976 that dislocation cores could act as the necessary precursors for martensitic embryos. More recently, Li *et al.* [**20**] have shown using molecular dynamics modelling that arrays of dislocations do give rise to the conditions conducive to the nucleation of martensite. Once the martensite is nucleated, the transformation will propagate through the austenite grain. VSR may be seen as a grain-by-grain stress reduction process, dependent upon the fact that some grains will transform immediately, while others will not transform until many cycles of applied stress eventually create the conditions for the creation of a martensite nucleus.

The application of VSR to structures has to date been a matter of trial and error; however, given an alloy composition and the details of the welding process, it is now possible to predict the phase composition that will result from a specific cooling regime. By this means, one may identify those structures which will respond readily to VSR, by computing the extent of retained austenite in the as-welded fabrication and its state of stability.

8 CONCLUSION

There is a body of experimental evidence to show that large welded fabrications may be stabilized by the application of resonant vibration which induces low levels of stress (in the range 5–10 per cent of the yield stress). The reduction in residual stress which is accomplished by the vibration cannot be explained in this case by the plasticity theory that has been developed to explain the operation of VSR in small specimens.

It has previously been shown that the martensite reaction may be stabilized so that small grains of austenite may exist at room temperature. A revised theory of VSR has been proposed based around the concept that the vibration activates mobile dislocations, so that they move into configurations that promote the nucleation of martensite in these grains of retained austenite, allowing the austenite to transform. When the austenite transforms to martensite, it undergoes a shear transformation which will act to reduce the local residual stress by interaction with the stress field imposed externally on the austenite grain. The use of VSR on large fabrications may then be seen to be related to the slow cooling rate of the structure, after welding, which promotes the stabilization and retention of the austenite. In smaller welded specimens, of the type used in laboratory investigations, the cooling rate is much higher, and the carbon does not have time to diffuse from the ferrite phase, which is a necessary step in the stabilization of the austenite grains. In specimens where the residual stresses are induced by cold working, there will be no retained austenite for the proposed mechanism to operate, and so these specimens conform to the plasticity theory of VSR.

By the use of modelling software, it should now be possible to predict alloy compositions and process variables which would predispose a structure to the useful application of VSR.

REFERENCES

1 **McGoldrick, R. T.** and **Saunders, H. S.** Some experiments in stress relieving castings and welded structures by vibration. *J. Am. Soc. Naval Eng.*, 1943, **55**(4), 589–609.

2 **Dawson, R.** and **Moffat, D. G.** Vibratory stress relief: a fundamental study of its effectiveness. *J. Eng. Mater. Technol.*, 1980, **102**, 169–176.

3 **Adams, C. M., Berry, J. T.,** and **Klauba, B. B.** Productive applications of mechanical vibrations. In *Trends in welding research* 2005, Pine Mountain, Georgia, 16–20 May 2005 (ASM International, Materials Park, Ohio), available from www.airmatic.com

4 **Mordfin, L.** (Ed.) *Mechanical relaxation of residual stresses*, ASTM STP 993, 1988 (American Society for Testing and Materials, Philadelphia).

5 **Gnirss, G.** Vibration and vibratory stress relief. Historical development, theory and practical application. *Weld. World*, 1988, **26**(11/12), 284–291.

6 **Munsi**, **A. S. M. Y.** *Investigation and validation of vibratory methods for stress relief and weld conditioning*. PhD thesis, University of Strathclyde, UK, 1999.

7 **Rao, D., Ge, J.,** and **Chen, L.** Vibratory stress relief in manufacturing the rails of a Maglev system. *Trans. ASME, J. Mf. Sci. Technol.*, 2004, **126**, 388–391.

8 **Sonsino, C. M., Muller, F., de Back, J.,** and **Gresnigt, A. M.** Influence of stress relieving by vibration on the fatigue behaviour of welded joints in comparison to post-weld heat treatment. *Fatigue Fract. Eng. Mater. Struct.*, 1996, **19**(6), 703–708.

9 **Walker, C. A., Johnstone, D.,** and **Waddell, A. J.** Vibratory stress relief – an investigation of the underlying processes. *Proc. IMechE Vol 222 Part E: J. Process Mechanical Engineering*, 1995, **209**, 51–58.

10 **Withers, P. J.** and **Bhadeshia, H. D. K. H.** Residual stress. Part 2 – Nature and origins. *Mater. Sci. Technol.*, 2001, **17**, 366–375.

11 **Francis, J. A., Bhadeshia, H. K. D. H.,** and **Withers, P. J.** Welding residual stresses in ferritic power plant steels. *Mater. Sci. Technol.*, 2007, **23**, 1009–1020.

12 **Shi, W., Zhang, X.,** and **Liu, Z.** Model of stress-induced phase transformation and prediction of internal stresses of large steel workpieces during quenching. *J. Phys. IV France*, 2004, **120**, 473–479.

13 **Ferguson, B. L., Li, Z.,** and **Freborg, A. M.** Modeling heat treatment of steel parts. *Comput. Mater. Sci.*, 2005, **34**, 274–281.

14 **Berrahmoune, M. R., Bervillier, S., Inal, K., Moulin, A.,** and **Patoor, E.** Analysis of the martensitic transformation at various scales in TRIP steel. *Mater. Sci. Eng. A*, 2004, **378**, 304–307.

15 **Munsi, A. S. M. Y., Waddell, A. J.,** and **Walker, C. A.** Modification of residual stress by post-weld vibration. *Mater. Sci. Technol.*, 2001, **17**, 601–606.

16 **Munsi, A. S. M. Y., Waddell, A. J.,** and **Walker, C. A.** Vibratory weld conditioning: treatment of specimens during cooling. *Proc. IMechE Part L: J. Materials: Design and Applications*, 2000, **214**(3), 129–138.

17 **Porter, D. A.** and **Easterling, K. E.** *Phase transformations in metals and alloys*, 1988 (Van Nostrand Reinhold (Int.), New York).

18 **Bhadeshia, H. D. K. H.** Some phase transformations in steels. *Mater. Sci. Technol.*, 1999, **15**, 22–29.

19 **Olson, G. B.** and **Cohen, M.** A general mechanism of martensitic nucleation: Part I. General concepts and the FCC → HCP transformation. *Metall. Trans. A*, 1976, **7**(12), 1905.

20 **Li, B., Zhang, X. M., Clapp, P. C.,** and **Rifkin, J. A.** Molecular dynamics simulations of the effects of defects on martensite nucleation. *J. Appl. Phys.*, 2004, **95**(4), 1698–1705.

21 **Wang, J.** and **van der Zwaag, S.** Stabilization mechanisms of retained austenite in transformation-induced plasticity steel. *Metall. Mater. Trans.*, 2001, **32 A**, 1527–1539.

22 **Turnbull, D.** and **Vonnegut, J. A.** Nucleation catalysis. *Ind. Eng. Chem.*, 1952, **44**, 1292.

23 **Bai, D. Q., di Chiro, A.,** and **Yue, S.** Stability of retained austenite in a Nb microalloyed Mn-Si TRIP steel. *Mater. Sci. Forum*, 1998, **284–286**, 253–266.

24 **Jimenez-Melero, E., van Dyke, N. H., Zhao, L., Seitsma, J., Offerman, S. E., Wright, J. P.,** and **van der Zwaag, S.** Martensitic transformation of individual grains in low-alloyed TRIP steels. *Scripta Mater.*, 2007, **56**, 421–424.

25 **Taljat, B., Radhakrishnan, B.,** and **Zacharia, T.** Numerical analysis of GTA welding process with emphasis on post-solidification phase transformation on residual stress. *Mater. Sci. Eng. A*, 1998, **246**, 45–54.

26 **Becker, M., Jordan, C., Lachhander, S. K., Mengel, A.,** and **Renaud, M.** Prediction and measurement of phase transformations, phase dependent properties and residual stresses in steels, OSTI report no. 8550544, May 2005.

27 **Bouville, M.** and **Ahluwalia, R.** Interplay between diffusive and displacive phase transformations: time-temperature-transformation diagrams and microstructures. *Phys. Rev. Lett.*, 2006, **97**, 055701–1–4.

28 **Lusk, M. T., Wang, W., Sun, X.,** and **Lee, Y.-K.** On the role of kinematics in constructing predictive models of austenite decomposition. In *Austenite formation and decomposition* (Eds E. B. Damm and M. J. Merwin), 2003, pp. 311–332 (MMM Society Warrendale, Pennsylvania).