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Metall entspannen mit Vibration

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Vibration and vibratory stress relief. Historical development, theory and practical application

by Dr. G. Gnirss (FRG)

1. Historical development

1.1. Base metal tests

At the beginning of the 1960s awareness grew of the possibility of replacing stress relief by vibrations. This was because since the mid 1950s [1] so-called vibration devices had been marketed which were intended to lead to an extensive reduction of residual stresses. Systematic tests conducted with this in mind by Bühler and Pfalzgraf [2] as well as by Zeig [3] could however only give limited confirmation of the promised effect. Although it is agreed that a reduction of residual stresses is basically possible, it is also said that with complicated components it would hardly be possible to fulfill the necessary requirements, not even with vibrations at natural frequency. It is pointed out, however, that with vibrations at natural frequency greater stress amplitudes arise, and the loads with vibration at a higher temperature can be less. However, it is also stressed that this is not admissible because of the danger of fatigue cracking. The outstanding significance of vibration amplitude compared with vibration time had, at that time, already been emphasized. A similarly negative attitude is also expressed in VDG memorandum No. 1, 1964 Edition [5] for castings. The reasons given there are based on the arguments mentioned above, such as the danger of fatigue cracking with the required high fluctuating loads and the uneveness of the stress reduction because of the complexity of the parts.

Concurrent tests carried out in Eastern Europe on aluminium rings [6, 7] also showed that the vibration amplitude is of primary sighificance and that the necessary minimum level can be generated by vibrations in the resonance range. Lokshin obtained this result through systematic testing of the influence of frequency, duration of treatment and acceleration, and he summarizes as follows: "A vibration treatment with resonance conditions can effectively reduce the internal stresses, particularly with parts made of thermally stabilized alloys. It is clear that a local relaxation of stresses during a vibration treatment disturbs the balance of the internal macrostresses in the body of the part, and also leads to a redistribution and reduction of stresses." Further Russian tests were carried out on grey cast iron by Adoyan [8, 9]; critical minimum loads were thereby determined for a residual stress reduction and these were brought into relation with the Smith diagram. Two ranges are obtained there: one in which a reduction of residual stresses should be possible, and another in which fatigue cracking must be expected during the vibration treatment. The statements made on the treatment time confirm the generally held opinion that a reduction in stress is at first large and later small. Even so it is still given in hours.

Whereas until then the stress reduction was the focus of interest, Adoyan [9] and Skazhennik [10] inspected the dimensional stability affected by residual stresses in the finishing of cast iron parts and the positive effect on them of vibration.

Woznay and Drawmer [11] used shot-peened samples as evidence of the effect of cyclic loading. Their tests show that residual stresses can be changed at sufficiently high cyclic loads, but that for this the yield point must be exceeded. At the same time the significance of the cyclic yield point on the stabilization of dynamically hardened or softened materials is pointed out. Working from this, a suggestion is made as to how the extent of the reduction in residual stresses can be predicted with the knowledge of the cyclic yield point (Fig. 1).

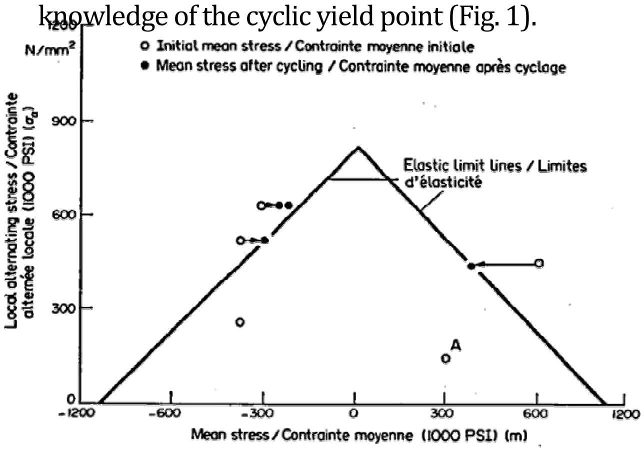

Fig. 1. Local alternating stress as a function of the mean stress

Wohlfahrt had already commented on the significance of the 0.01% proof stress. According to his investigations, a reduction in the residual stresses was evident with stress amplitudes (vibration and residual stresses of first order) <$R_{p0.01.}$ This can be explained by the fact that the residual stresses of second and third order were superimposed on those of first order and they caused the yield point to be exceeded even if the residual stresses of first order were still below it. They also emphasize that a threshold value for the vibration stressess must be exceeded, and that the reduction in residual stresses is particularly great with the first cyclic bending loads.

A further basic investigation is described by Dawson and Moffat [13]. They also observed the vibration treatment and the related residual stress rearrangements by means of strain gauges. They produced the residual stresses by bending sheet metal strips of hot and cold-rolled steel and of aluminium alloy, as Pattinson and Dugdale [14] had already done previously. As already reported several times in the relevant literature, this showed no influence from the natural frequency under investigation. But they did also find an amplitude threshold value which must be exceeded for a relief of residual stresses. For an almost absolute reduction in residual stresses, amplitudes at the level of 0.8 x $R_{p0.2}$ were necessary. An indirect result of this is that the sum of vibration amplitude + residual stress of first order can still be less than $R_{p0.2}$, which indicates microcreep in the range of $R_{p0.1}$ or emphasizes the significance of the cyclic yield point. Their tests further confirm that the residual stress relief of non strain-hardened steels tends to occur in the first phase of the vibration treatment. They talk of >75% residual stress relief in the first 10 load cycles. This would allow short treatment times (<15 min), so that fatigue strength problems are not a serious worry in view of the smaller numbers of load cycles with common treatment frequencies (<100 Hz), these numbers being below the base load cycles of 10^6 for the fatigue strength chart. This is important because the amplitude threshold values established are within the range of the fatigue strength. Their results are summarized in a diagram (Fig. 2), which had already been used in a similar way in [11] (Fig. 1). Reference was however made to the cyclic yield point.

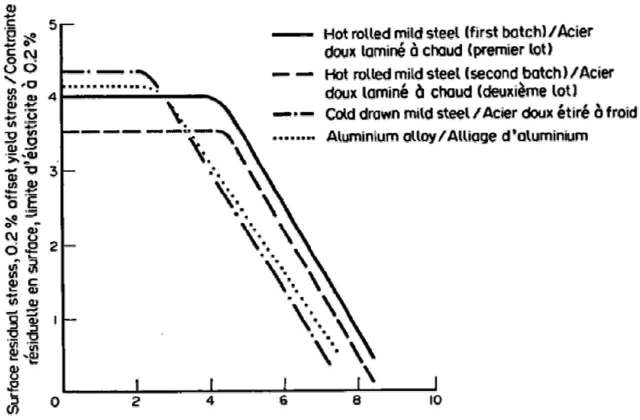

Fig. 2. Residual stress as a function of the cyclic strain amplitude

1.2. Investigation of the welded joints

Once it had basically been demonstrated that residual stress relief is possible in the base metal, it was clear that the transferability to welds had to be shown.

A test to relieve residual stresses which had occurred through the welding of a plate into a frame failed, however [11], which again highlighted the problem of the transfer of model results to components. The result expected by the manufacturer of the vibrator, that is a residual stress relief within 10 minutes, did not occur even with vibration with resonance frequency at the selected measuring point.

Rich showed in [15], just as Bühler and Pfalzgraf had previously done in [4], that residual welding stresses are, however, basically reducible. After 15 minutes vibration at the first resonance frequency he was also able to obtain clear residual stress relief on both ferritic and austenitic sheet-metal strips, to which bead-on-plate runs had been applied to produce residual stresses. According to his data, the total of residual stress and vibrational stress was still below the fatigue strength in the Smith diagram. The vibration stress here was clearly less than the residual stress.

S. Weiss and co-authors [16] also concentrated on welds. With resonant vibration at high stress amplitude, which were observed by using strain gauges, their tests with circular seams on sheet metal also showed a clear change in the radial and axial residual stresses at an earlier stage of the vibration. Since the residual stresses were at the level of the yield point before the vibration, and vibrational amplitudes of between 50% and 100% x $R_{p0.2}$ were applied, local creep must be assumed. The vibrations here lasted 15 minutes at about 130 Hz. As the result of their investigations, the authors also point out that their results may only be transferred to similar soft materials, as otherwise there is a danger of fatigue strength problems with crack formation. They also point out that, with complex structures, it is difficult to control the application of sufficiently high stress amplitudes during the vibration at the points where a residual stress relief is required.

In [17-19] it is reported that vibrational stress relief can also be successfully applied during welding. The slighter distortion of the welded structures is explained by the greater mobility of the displacements at higher temperatures during the welding process itself. It is also important to note that, for residual stress relief, the technical macroscopic yield point must not be observed; strains exceeding of 0.1% should certainly be sufficient to produce yielding.

2. Theory

Pusch tried to explain the behaviour from the metallurgical point of view [20]. He points out the reduction in the damping during the vibrational stress relief and judges this to be a sign of residual stress relief in the form of the elimination of displacements. This is said to be revealed in a reduction of the motor current from the vibration equipment, and hence makes possible statements on the effectiveness of the treatment. This technique is also applied to some vibration equipment as evidence of successful treatment.

The hypotheses used today to explain residual stress relief are given in a summarized form in [21]. This document is concerned firstly with the opinion represented by Kelso [22], according to which the lattice or interstitial atoms in disorder can be put into a stable condition by means of additional energy, which amounts to a change in the residual stress situation. This can be by means of heating or mechanical vibration. The most widely held opinion is based on the assumption that the residual stress and vibrational stress together exceed the yield point and so a plastic deformation occurs with the residual stress relief. A distinction is drawn here between cyclically hardening and softening materials.

A further theory is put forward by Sudnik and Jarlyko. They gave prominence to the microplastic flow and highlighted this with the help of a normalized fatigue strength diagram (Fig. 3).

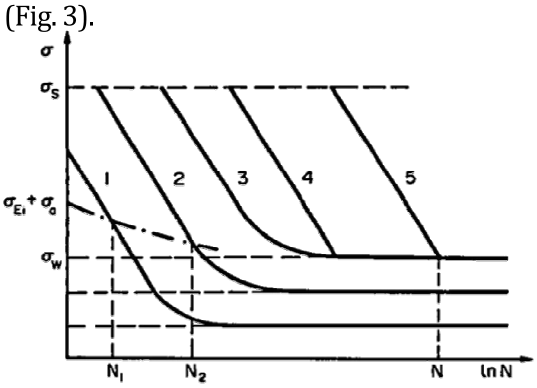

Fig. 3. Total fatigue diagram and kinetics of residual stresses relief. 1. Microscopic flow initiation line; 2. macroscopic flow initiation line; 3. macroscopic flow term initiation line; 4. submicroscopic fractures initiation line; 5. fatigue fracture curve; δ_{Ei}, = residual stresses; δ_a= vibrational stress

As a result of residual stress and superimposed vibrational stress, microplastic flow occurs after a sufficient number of cycles N_1, which with further vibrations leads to residual stress relief. The higher the vibration amplitude becomes, the more the residual stress is reduced, according to them, the vibration must be broken off by N_2 at the latest in order to avoid fatigue damage.

3. Areas of application

The authors envisage possible areas of application for vibrational stress relief not only in the relief of residual tensile stresses to prevent brittle fractures, but also in cases where the relief of residual surface stresses is required owing to the risk of stress corrosion cracking and to ensure the maintenance of dimensional stability in machining. It was reported recently in [23-25] that good results have been achieved in the latter objective. But there are also more recent negative reports as well [26].

An industrial application of vibrational stress relief is described in [27]. A comparison of the residual stresses in gear-boxes which were untreated, heat treated and treated by vibration showed that those not subjected to heat treatment clearly presented the highest level; the stresses in the heat treated gear-boxes only amounted to 17%, and those in the boxes treated by vibration to approximately 35%. A definitely positive effect was thereby established.

A further test was dealt with more recently in [28]. In this, circumferential welds on pipe lengths in a non heat-treated condition were checked for comparison after stress relieving and after vibration treatment during and after welding. In short, it can be said that the vibration treatment produced the expected improved dimensional stability in the assembly.

Although the toughness in the heat-affected zone seems to indicate that the transition temperature decreased slightly as a result of the vibration treatment, the CTOD values influenced by relief of residual stresses showed an increase. As expected, the hardness was not affected. However, in assessing the results it should be noted that the changes in characteristics are not underpinned statistically.

The most up-to-date reference to dimensional stabilization by vibrational stress relief and the theory behind it is given in [34]. The author states that there is no marked reduction in welding stresses but a very pronounced effect on dimensional stability. The mechanism behind these phenomena seems to be not the sum of the internal and vibrational stresses, which are in the range up to 50 MPa, but some effect similar to natural ageing.

Another recently published document [35] deals with stress relief, dimensional stability, the effect on toughness and fatigue strength due to vibratory stress relieving. The findings show again that the shape of the fabrication is stabilized and that there is no negative effect on strength, toughness and fatigue behaviour. The vibratory stress relief process is proposed and also used for lowering residual stresses. Unfortunately the boundary conditions which have to be kept in mind are not given clearly enough.

A critical assessment of most of the results given in the literature is not possible, because no sufficiently precise data have been reported. In this respect, the value of the summarized descriptions as presented in [29-33] is unfortunately, limited.

4. Summary

From the current point of view the following can be said by way of summary:

1. Areas of application of vibrational stress relief include the following

(a) dimensional stabilization during machining

(b) avoidance of stress corrosion cracking through reduction of surface tensile stress

(c) reduction of risks during welding

(d) reduction of the residual stress level for welded structures.

2. If a significant reduction of the residual stress level is required, unestablished minimum values of the stress amplitudes are not necessary in vibrational stress relief. With the equipment available, these are probably only reached with vibration at resonance frequency.

3. If residual stress relief of whole components or weld seams is to be achieved, the vibrations must be at several frequencies because the necessary stress amplitudes can otherwise only be generated within localized limits.

4. If a residual stress reduction with high amplitudes is achieved within fewer load cycles, the vibration time can be kept short in order to minimize fatigue strength problems. This applies in particular, because the level of the stress amplitudes obtained on the component cannot be predicted. A check using strain gauges would generally not be accepted for reasons of cost.

5. The reduction in damping could be taken as a measure of the integral effect of the vibration. However, this yields no information on the stress relief in weld seams.

6. Since the success of the vibration treatment can be demonstrated relatively easily in the

form of the improvement in dimensional stability during machining, the process is applied there with positive results. But many questions still remain unanswered. With the objectives "stress relief for reasons of corrosion or toughness after welding" or "reduction of the risk of cracks during welding", the process has not yet made significant headway because the transfer of the positive results from basic investigations to components still poses too many unanswered questions. Thus, for example, there is no knowledge of the locally developed vibration amplitudes and the residual stress relief is not quantifiable. For that reason, a clear doubt as to the practical applicability of residual stress relief of weld seams is also expressed in the DVS-work sheet 1002/T.2/1986 [34], entitled "Procedure for reducing residual welding stresses".

In this respect, even with monitoring of the motor current, the procedure can be used only for series fabrication, where identical components can always be assumed after a basic calibration. Similarly favourable conditions could also apply for circumferential pipe seams.

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