Investigation of residual stress relaxation on Cr12MoV steel under high-frequency cyclic loading

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Abstract. High frequency vibratory stress relief (VSR) is a procedure to reduce the residual stresses by means of high frequency cyclic dynamic stress. Cyclic loading, or cyclic dynamic stress, imposed on the workpieces during the high frequency VSR affects the reduction of the residual stresses. In this study, the high frequency VSR was carried out on the Cr12MoV steel quenched specimens. And the residual stresses on the Cr12MoV steel surface before and after the high frequency VSR were studied by the hole-drilling method. The results show that the residual stresses can be effectively reduced by the high frequency VSR. Moreover, increasing the high frequency vibration frequency and the high frequency vibration amplitude can improve the effect of the high frequency VSR.

1. Introduction
Residual stress can be induced by assembly and machining processes such as welding, rolling, cutting, grinding and casting. Residual stress may shorten the fatigue life of the workpiece [1] through increasing the fatigue crack growth rate [2]. Thus, residual stress relief process has attracted increasing interests from both industrial and academic communities recently. Among different stress relief processes used today, VSR has been the most preferred method for eliminating the residual stresses, which has many advantages such as better effect, environmental protection, less investment, energy saving and shorter processing time. In the applications of the conventional low frequency VSR [3–6], it is clear that a speed-adjustable motor is adopted as the exciter and the vibration frequency is less than 200 Hz in conventional stress relief by vibration. In the meantime, the exciter is too big to be installed with a small workpiece. Especially with the further studies of residual stresses of MEMS [7], the limitation of conventional low frequency VSR becomes more and more apparent.

Considering the shortcoming of the conventional low frequency VSR, He et al. putted forward the basic idea of high frequency VSR [8] in which an electromagnetic vibration exciter was adopted as the exciter. Small workpiece can be installed on the vibration table conveniently [9] and the vibration frequency can reach 10 kHz. Jiang et al. [10] relieved the residual stresses of a welded structure with the size of 230 mm×105 mm×9 mm. The specimen was vibrated at 2251 Hz and the peak residual stress
decreased by about 54%. Thus, the high frequency VSR is hopeful to eliminate the residual stresses of workpieces, especially to small workpieces such as MEMS.

In this study, the high frequency VSR with different process parameters was carried out on the Cr12MoV steel quenched specimens. And the residual stresses on the Cr12MoV steel surface before and after the high frequency VSR were studied by the hole-drilling method.

2. Materials and experimental methodology

2.1. Materials and specimens
The specimens used in the high-frequency VSR experiments are prepared from the Cr12MoV steel, whose size is 60 mm×20 mm×6 mm as shown in Figure 1. The residual stresses in the Cr12MoV steel specimens are induced by 950°C oil quenching.

2.2. Hole drilling method for residual stress measurement
The residual stresses in the Cr12MoV steel quenched specimens surface are evaluated by the hole drilling method [11]. Two residual stresses measured points 1 and 2 are respectively selected as shown in Figure 2 to obtain the residual stresses in the same specimen before and after the high frequency VSR. The two strain rosettes are respectively attached to the specimen surface at the measured points 1 and 2 to obtain the relieved strains surrounding the drilled hole. In this case, the x axial and y axial stresses $\sigma_x$ and $\sigma_y$ in the specimen surface can be given as [11]

$$
\begin{align*}
\sigma_x &= \left( \frac{E}{2(1+\nu)\bar{a}} - \frac{E}{2b} \right) \varepsilon_1 + \left( \frac{E}{2(1+\nu)\bar{a}} + \frac{E}{2b} \right) \varepsilon_3, \\
\sigma_y &= \left( \frac{E}{2(1+\nu)\bar{a}} - \frac{E}{2b} \right) \varepsilon_1 + \left( \frac{E}{2(1+\nu)\bar{a}} + \frac{E}{2b} \right) \varepsilon_3,
\end{align*}
$$

(1)

In which $\nu$ is the Poisson’s ratio, $E$ is the Yong’s modulus, $\bar{a}$ is the calibration constant for isotropic stresses, $b$ is the calibration constant for shear stresses, $\varepsilon_1$ and $\varepsilon_3$ are the relieved strains respectively along the x axial and y axial direction. In this study, $\bar{a}$ and $b$ are respectively 0.192 and 0.482 according to the standard of the hole drilling method [11].

Figure 1. Schematic diagram of the Cr12MoV steel specimen.

Figure 2. Schematic diagram of two residual stresses measured points and attached strain rosettes.
2.3. High frequency VSR experimental system

The experimental system used for high frequency VSR experiments is shown in Figure 3. It mainly consists of a high frequency vibrator used for generating the high frequency vibration and a high frequency vibration amplitude amplifying device [12] used for installing the Cr12MoV steel specimen to be vibrated with larger high frequency vibration amplitude. The signal generator is controlled by the upper computer system to generate the high frequency vibration frequency, while the acceleration sensor is implemented to measure the output high frequency vibration amplitude of the high frequency vibration amplitude amplifying device directly applied on the Cr12MoV steel specimen. The high frequency vibration amplitude amplifying device [12] consists of a pallet, a connecting rod and a chassis.

![Figure 3. Schematic diagram of two residual stresses measured points and attached strain rosettes.](image)

3. Experimental results and discussions

3.1. Effect of vibration frequency on residual stresses relaxation

The x axial and y axial residual stresses of the five groups of the Cr12MoV steel specimens before and after the high frequency VSR with different vibration frequencies can be shown in Figure 4. The high frequency vibration amplitude is fixed for 5 μm, the high frequency vibration time is fixed for 25 min, while the high frequency vibration frequency is changed during the high frequency VSR, which is used to evaluate the effect of the high frequency vibration frequency on residual stresses relaxation. To improve the reliability of the experimental results, the three Cr12MoV steel quenched specimens were divided into the same group in this study. It can be found from Figure 4 that increasing the high frequency vibration frequency can improve the effect of the high frequency VSR.

![Figure 4. Effect of high frequency vibration frequency on residual stresses relaxation.](image)
3.2. Effect of vibration amplitude on residual stresses relaxation
The $x$ axial and $y$ axial residual stresses of the five groups of the Cr12MoV steel specimens before and after the high-frequency VSR with different vibration amplitudes can be shown in Figure 5. The high frequency vibration frequency is fixed for 2.4 kHz, the high frequency vibration time is fixed for 25 min and the high frequency vibration amplitude is changed during the high-frequency VSR, which is used to evaluate the effect of high frequency vibration amplitude on residual stresses relaxation. In order to improve the reliability of the experimental results, three Cr12MoV steel quenched specimens were divided into the same group as well. It can be found from Figure 5 that the effect of the high frequency VSR can be improved by increasing the high frequency vibration amplitude.

![Figure 5. Effect of high frequency vibration amplitude on residual stresses relaxation.](image)

3.3. Discussions
The initial residual stresses in the Cr12MoV steel quenched specimens are compressive stresses as shown in Figure 4 and Figure 5. As well known the quenched residual stresses are compressive stresses, which implies that the residual stresses measuring results are reliable. Furthermore, increasing the high frequency vibration frequency and the high frequency vibration amplitude during the high frequency VSR can improve the high frequency vibration energy imposed into the Cr12MoV steel quenched specimens. In this case, the dislocations inside the materials can be activated easily, which results in that the plastic deformation can be induced inside the materials. Under this condition, the residual stresses inside the materials can be reduced and improving the high frequency vibration frequency and the high frequency vibration amplitude can improve the effect of the high frequency VSR as shown in Figure 4 and Figure 5.

4. Conclusion
The high frequency VSR is introduced to reduce the residual stresses in the Cr12MoV steel quenched specimens. The residual stresses can be effectively reduced by the high frequency VSR. Moreover, the effect of the high frequency VSR can be improved by increasing the high frequency vibration frequency and the high frequency vibration amplitude.
Acknowledgments
This research is sponsored by the Shanghai Sailing Program (No. 18YF1409800), the National Natural Science Foundation of China for Young Scholars (Nos. 51605303 and 51805477) and the Postdoctoral Science Foundation of China (No. 2018M632453).

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