Investigations on the changed intensity shot peening specimens machined from SS304: process characterization, fatigue modeling, and failure analyses

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Received: 4 August 2021 / Accepted: 14 March 2022 / Published online: 24 March 2022
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Abstract
Characterization on the surface morphology, residual stress relaxation, and fatigue life prediction of the changed intensity shot peening specimens machined from SS304 were carried out. The present work aims, first and foremost, to model the fatigue performance of shot peening specimens machined from SS304 in extra-low-, low-, and high-cycle regime by clarifying the relaxation life component and fatigue life component with the total failure life, thereby successfully evaluating the fatigue performance of un-/0.1 mmA-/0.25 mmA-/0.4 mmA-peened components with satisfactory results in the whole cycle regime. It is, therefore, essential to provide a precise definition of the master life diagram on the purpose of evaluating the fatigue performance of shot peening components in service by linear interpolation of shot peening intensities considering the engineering applicability. Additionally, the characterization of multiple-fatigue crack initiation to failure was also identified by fractography analysis, which reasonably illustrated the non-conservative life prediction in the high-cycle regime.

Keywords Shot peening · Residual stress relaxation · Life transition behavior · A master life diagram · Multiple-fatigue initiation

1 Introduction
Introduction of shot peening to machined surface helps forming compressive residual stress, which plays a great role in improving fatigue performance. In view of this, shot peening is widely used in industry [1, 2], and the discussion on its process characteristics is also available in [3, 4].

Topics of shot peening are numerous, mainly including three aspects: 1) Process characterization, which helps measuring the shot peening intensity, characterizing surface morphologies as well as evaluating the residual stress; 2) Fatigue modeling, which requires experimental/numerical study on the service performance of shot peened components; 3) Failure analysis, which provides a verification for understanding the failure mechanism of shot peened components. Accordingly, around the main topics involved in shot peening and their relevance is shown in Fig. 1.

The 304 austenitic stainless steel (SS304) is one of the most widely used metallic materials and is processed into a variety of engineering structural components. Combined with shot peening treatments, its mechanical properties are further developed and play a more potential and valuable role in the practical service of engineering structures [5–7].

An enhanced fatigue performance by shot peening treatments has been systematically studied [8], including a serious of key issues on i) effect of variation of shot peening treatments on fatigue performance [9], ii) mechanism of residual stress relaxation caused by mechanical loading [10–12] and elevated thermal exposure [13], iii) failure of shot peened structure under complex loading conditions [14–16], iv) degradation of fatigue performance due to increased surface roughness and shape distortion by shot peening treatments [17–19], v) study on the fatigue performance of the shot peening components characterized with complex structures [14], etc. Others, namely, the material-dependent and numerical calculation-dependent key issues on shot peening treatments, are available in [20–22].
Although there are many reports on the fatigue performance of shot peened structures, the investigations on stress relaxation and failure under alternate loading need special attention. In light of this, a series of investigations have taken efforts to further study these issues. Important but not the foremost, Dalaei et al. [10] studied the influence of shot peening on fatigue durability of normalized steel subjected to complicated loading conditions, including overloading and variable amplitude loading along with their influence on fatigue lifetime. In addition to the effect of shot peening treatments on fatigue performance, Kim et al. [23] experimentally studied fatigue performance of specimens machined from medium-carbon steel. The fatigue performance of shot peening specimens as well as the accompanied stress relaxation process was analyzed in the low- and high-cycle regime. In a series of papers Benedetti and coworkers systematically studied the fatigue of shot peened aluminum alloys. Low-/high-/very high cycle fatigue of aluminum alloys was experimentally carried out, respectively [24, 25]. Moreover, most of the available investigations on bending fatigue of shot peened aluminum alloys were also mainly attributed to Benedetti and coworkers [14–16]. The most recently reports by Lèvesque et al. [26] highlight that defects in the structure and shot peening-induced surface roughness together degraded the fatigue resistance of the structure, which is of great significance because it has opened the prologue of the research on the surface integrity and damage tolerance of shot peened structures.

As it was reported that the main purpose of the introduction of shot peening treatments is to increase the service life of the structure by introducing compressive residual stress on the surface of the material, the strategy of which is to increase the total failure life by introducing and extending the relaxation life as significantly as possible. It is, therefore, essential to clarify the relaxation life component and fatigue life component with the total failure life of shot peening specimens subjected to cyclic mechanical loads. However, only experimental investigations on illustrating the failure behavior together with the compressive residual stress relaxation and the fatigue process were available in [10–12, 27], whereas the modeled description is urgently needed in terms of the failure process of shot peening components subjected to cyclic mechanical loads. Meanwhile, with the increase of shot peening intensities, the surface roughness of the structure increases significantly, thereby leads to and intensifies the stress concentration, which consequently accelerates the
release of residual stress and reduces the fatigue life. It is designated as life transition phenomenon, which commonly occurs in the extra-low-/low-cycle regime as experimentally revealed in [28–30]. It is, therefore, essential to try to describe the fatigue performance in the extra-low-/low-cycle regime so as to comprehensively indicate the effect of life transition phenomenon on life prediction in this regime.

With respect to the mentioned challenges of the effect of shot peening treatments on fatigue performance, this paper developed a unified model by clarifying the relaxation life component and fatigue life component with the total failure life and thereby successfully evaluated the fatigue performance of shot peening components in extra-low-, low-, and high-cycle regime and acquired satisfied life prediction results for various shot peening intensities. Based on the new proposed model accompanied with experimental investigation, the life transition phenomenon was also identified. Furthermore, a master life diagram on evaluating and predicting fatigue performance of shot peening specimens against various shot peening intensities in extra-low-, low-, and high-cycle fatigue life regime for SS304 was developed on purpose of predicting or evaluating the fatigue life and performance of shot peened structures in service by linear interpolation of shot peening intensities. Additionally, characterization of multiple-fatigue initiation to failure was identified by fractography analysis, which reasonably illustrated the non-conservative life prediction in high-cycle regime.

2 Experiments

2.1 Materials and specimens

The austenitic stainless steel 304 (SS304), a face-centered cubic structure (FCC), with chromium (chemical) content up to 17% and nickel (chemical) content about 8%, was studied in this paper and is presented in Table 1.

In order to avoid the data dispersion of material mechanical properties between specimens, all specimens were obtained from a single bulk of the material. The raw material was cut from one round bar with a diameter of about 210 mm. The raw material was cut by electrical discharge machining (EDM) which was solution treated at 1050°C for 30 minutes and water-cooled. The microstructure of SS304 is available in Fig. 2, which clearly illustrates the grain size of SS304 that ranges from 100 to 150 μm. The forging billet

| Table 1 Chemical composition of SS304 (wt.%) in the study |
|----------------|
| Fe  | C     | Si    | Mn    | P     | S     | Cr    | Ni    |
| Balanced | 0.04  | 0.41  | 1.05  | 0.035 | 0.003 | 17.1  | 8.1   |

Fig. 2 The microstructure of SS304 (200x, observed by polarizer)
of SS304 material was processed into tensile test specimens and fatigue test specimens, and the shape and dimension of them are shown in Fig. 3. All dimensions of specimens are in millimeters.

### 2.2 Shot peening treatments and performance characterization

With regard to the processing, shot peening is a multi-factor coupling process, which includes shot material and geometry, shots material and size, shot peening equipment, and parameters, etc. Different shot peening intensities can be obtained by changing the above parameters. Figure 4 shows the internal conditions of shot peening equipment, shot peening pressure indicator, and finished products during the shot peening process. Moreover, Table 2 also lists necessary details on the operating conditions and parameters during shot peening process.

Investigations [31, 32] indicated that the shot peening-induced surface morphology of components degraded the fatigue performance since the surface might seriously distorted. As illustrated in Fig. 2, the variation of shot peening intensity in this study is realized by changing the shot peening pressure. Increasing the shot peening pressure will lead to deeper craters and aggravate the surface state (roughness), thus introducing micronotches. Therefore, the increase of shot peening intensity will increase the stress concentration on the shot peened surface. In other words, even if there is no macronotch on the specimen, the micronotch caused by shot peening to destroy the surface integrity is also the essential cause of stress concentration. Characterization of morphologies of specimens machined from SS304 with different shot peening intensities, namely un-, 0.1/0.25/0.4 mmA-peened based on the white-light interference measuring technique (ZYGO NexView, America, RMS repeatable precision of 0.005 nm, vertical scan range from 0 to 20 mm, vertical resolution of 0.1 nm and test accuracy of $R_s \leq 0.1 \text{ nm}$), are presented in Fig. 5, respectively. Meanwhile, quantized 3D morphologies including surface roughness parameters such as the notch depth ($\alpha$) and the notch width ($2\beta$) were statistically characterized and are presented in Fig. 6. The data show that although there is, in fact, an identically increasing trend for both $\alpha$ and $\beta$ against shot peening intensities, the notch width exhibits increasing rates considerably higher than the notch depth data. Accordingly, Li et al. [33] correlated the notch characteristics with the stress concentration factor $K_t$ based on an empirical expression:

$$K_t = 1.0 + 4.0 \left( \frac{\alpha}{2\beta} \right)^{1.3},$$

which was commonly applied in characterizing the shot peening morphologies [34, 35]. Illustration on the correlation between stress concentration factors and shot peening intensities calculated by Eq. (1) is also available in Fig. 6, which is well-described by...
$K_i = \eta_0 + \eta Q^{\gamma}$, 

with $\eta_0=1.0$, $\eta=0.265$, and $\gamma=0.2$, respectively.

The residual stress of specimens was measured by the X-ray Stress Analyser (LXRD, Proto, Canada) with Mn-K$_\alpha$ radiation, voltage of 30 kV, current of 20 mA, Cr filter, and 311 diffraction plane (hkl) by using $\sin^2\psi$ method. The $hkl$-depended X-ray diffraction elastic constants adopted here were $7.18 \times 10^{-6}$ MPa$^{-1}$ and $-1.20 \times 10^{-6}$ MPa$^{-1}$.

### Table 2

| Conditions | Parameters and properties |
|------------|---------------------------|
| Materials  | Shot SS304 ca.50HRC        |
|            | Shots Cast iron ca.50-60HRC|
|            | Almen Magnesium alloy 76.1mm×18.95mm×1.295mm |
| Pressure   | 0.1mmA 0.05MPa            |
|            | 0.25mmA 0.23MPa           |
|            | 0.4mmA 0.3MPa             |
| Flow       | 8kg/min                   |
| Time       | 20sec                     |
| Nozzle     | Inner diameter 10mm       |

respectively. About the residual stress measurement, the range of tilting angles (psi) is $0^\circ$ - $\pm45^\circ$. Moreover, in-depth residual stress distribution of shot peened specimens is also required. Generally, the samples were electrochemically exfoliated by electropolishing machine, in which the electrolyte was saturated salt water, the working parameters of DC power supply were 15 V and 2 A, and the depth of electrochemistry corrosion was detected by digital micrometer. Accordingly, in-depth residual stress distribution of as-treated specimens is depicted in Fig. 7.

The overall trends, apparently, are the same, but the remnant compressive residual stresses are completely different. The maximum compressive residual stresses $\sigma_{\text{max,initial}}^R$ termed of in-depth value along the spoon-like curves were designated as the initial values to resist fatigue failure. Therefore, the relationship between the initial compressive residual stress and shot peening intensities is illustrated and correlated by

$$\sigma_{\text{max,initial}}^R = \mu Q^{\xi}$$

with satisfactory fitting results, where $\mu=861$ and $\xi=0.181$ are both fitting parameters, which represent the residual stress characteristics introduced by specified shot peening process formulated in Table 2 on the surface of the specimen machined from SS304.
2.3 Mechanical properties of SS304

Monotonic tensile tests were carried out to acquire the basic mechanical properties of SS304. Engineering stress/strain curves in terms of un-/0.1 mmA-/0.25 mmA-/0.4 mmA-peened specimens in monotonic tensile tests are presented in Fig. 8, together with a detailed description in the earlier loading regime. The MTS-809 test system with an axial loading capacity of ±250kN equipped with non-contact laser extensometer was used to avoid additional damage on the peened surface. The solid round bar specimens (Fig. 3a) were tested and recorded in displacement control mode with a rate of 0.01 mm per second. The strong similarity between tensile curves of various shot peening intensities indicates a surface-independent monotonic tensile properties of SS304. Therefore, monotonic parameters (ultimate stress $\sigma_u$, yield stress $\sigma_y$, Young’s modulus $E$, reduction in area $\psi$, elongation $\delta$, Poisson’s ratio $\nu$) of SS304 with errors are available in Table 3. Cyclic parameters such as $K_i^\prime$ and $n^\prime$ are referenced from [36]. Based the above parameters with regard to the monotonic and cyclic tests, parameters in terms of the fatigue properties, namely $\sigma_f$ and $b$, can be calculated by using the method in [37].

2.4 Fatigue testing and S-N curve

Sinusoidal ($R = -1$) load-controlled uniaxial fatigue tests were also performed with MTS-809 test system to evaluate the stress/strain responding during cyclic loading at room temperature and nominal frequency of 5 Hz. Various stress amplitudes corresponding to fatigue lives in the extra-low-, low-, and high-cycle regime were considered for un-/0.1 mmA-/0.25 mmA-/0.4 mmA-peened specimens. Fatigue tests were terminated when specimens completely fractured or the number of cycles exceeded $10^6$. The number of un-/0.1 mmA-/0.25 mmA-/0.4 mmA-peened specimens is 15, 9, 11, and 13, respectively, based on which $S-N$ curves with different shot peening intensities can be obtained.
3 Results and discussion

3.1 Failure life prediction scheme for shot peening specimens subjected to cyclic mechanical loads

Fatigue performance of shot peening structures subjected to alternate loads is characterized with sophisticated mechanism since the damage caused by residual stress relaxation and fatigue is hardly to clarify. It is, therefore, essential to try to describe the total failure life \( N_T \) of shot peening specimen by dividing the total life into two parts, namely the relaxation life \( N_{Rf} \) and fatigue life \( N_{Ff} \) as

\[
N_T = N_{Rf} + N_{Ff},
\]

in which the total life accords with the order of stress relaxation followed by fatigue failure. Strictly speaking, however, the damage caused by stress relaxation and fatigue will occur in the whole stage of cyclic loading. Additionally, the effect of relaxation is mainly in the initial stage of cyclic loading and gradually decreases with the progress of cyclic loading, while the effect of fatigue is mainly in the medium-long stage of cyclic loading and gradually increases with the progress of cyclic loading. In order to clarify the relaxation life and fatigue life from the total failure life so that the issue can be settled reasonably, Eq. (4) is recommended in this paper.

3.2 Characterization of residual stress relaxation process of shot peening specimens

Characterization of residual stress relaxation process of shot peening specimens has been discussed in some detail, e.g., in [11, 12, 27], among which the power criterion developed by Zhuang et al. was proved to give better description of residual stress evolution process by considering the effect of stress ratio and mechanical cyclic amplitude as well as the rapid relaxation behavior of residual stress in the first or first few cycles [27]. Initially, the power criterion proposed by Zhuang and Halford expressed as

\[
\frac{\sigma_{Rmax}}{\sigma_{Rmax,initial}} = \alpha \left[ \frac{2}{1 - R} \left( \frac{\sigma_a}{\sigma_y} \right)^2 \right]^\rho (N_{Rf}^{R} - 1)^\kappa - 1,
\]

where \( \sigma_{Rmax} \) is the maximum compressive residual stress along the depth direction from the peened surface, \( R \) is the stress ratio, and \( \sigma_a \) is the nominal stress amplitude introduced by cyclic mechanical loading. Moreover, \( \alpha \), \( \rho \) and \( \kappa \) are fitting parameters indicating the relaxation characteristics, \( N_{Rf}^{R} (= N_{Rf} + 1) \) refers to the abscissa of the coordinate system corresponding to Eq. (5). This operation of adding 1 to the value of relaxation life \( N_{Rf}^{R} \) is very meaningful, because it meets the requirements of describing relaxation process completely in logarithmic coordinate system. Apparently, before cyclic loading, namely \( N_{Rf}^{R} = 0 \) and \( N_{Rf}^{R} = 1 \), Eq. (5) can be simplified to \( \sigma_{Rmax}^{R} = -|\sigma_{Rmax,initial}^{R}| \text{ or } \sigma_{Rmax}^{R} = \sigma_{Rmax,initial}^{R} \).

Degradation of fatigue life induced by deterioration of surface morphology after peening treatments has been highlighted and experimentally reported [11, 12, 27]; however, correlation between the shot peening intensities and residual stress relaxation behavior still needs further investigation. In light of this, \( K_t \), the stress concentration factor induced by peening treatments, was introduced to correlate the peened surface morphologies with the mechanical loads, which can be expressed as

\[
\sigma_{max}^{M} = K_t \sigma_{max}^{M},
\]

where \( \sigma_{max}^{M} \) is the nominal stress of the peened specimen subjected to mechanical loads, \( \sigma_{Rmax}^{M} \) is the maximum mechanical stress of the peened surface considering the stress.
concentration behavior. Substituting Eq. (6) into Eq. (5) yields the surface-dependent residual stress relaxation criterion as

\[
\frac{\sigma_{\text{max}}}{\sigma_{\text{max, initial}}} = \alpha \left[ \frac{2}{1 - R} \left( \frac{K_m \sigma_y}{\sigma_y} \right)^2 \right]^\rho \left( N_R - 1 \right)^\kappa - 1,
\]

\[
\sigma_R = \alpha \left[ \frac{2}{1 - R} \left( \frac{K_m \sigma_y}{\sigma_y} \right)^2 \right]^\rho \left( N_R f \right)^\kappa - 1,
\]

Figure 9 gives schematic (Fig. 9a) and experimental (Fig. 9b, c, and d) illustrations on the relaxation process of shot peening specimens subjected to various mechanical cyclic loads. As it is shown in Fig. 9b, c, and d that when the applied mechanical stress is greater than the fatigue limit or even the yield strength, the compressive residual stress will relax obviously after the first cycle and then start to relax steadily. With the linear increase of the fatigue cycles (note that the abscissa in Fig. 9 is in the form of logarithmic coordinate), the relaxation rate of residual stress will gradually decrease. When the residual stress is relaxed to 10% of the initial value \( \sigma_{\text{max}} / \sigma_{\text{max, initial}} = 0.1 \), it can be considered that the relaxation process is completely stable. At this time, fatigue begins to be the main factor leading to the failure of the peened specimens. It should be noted that measurements on residual stress evolution versus mechanical fatigue cycles up to \( 10^4 \) were carried out in this study, which presented strong linear trend in a considerable life range. However, it is necessary to measure the residual stress at higher cycles (more than \( 10^6 \)), which may improve the predicted accuracy of residual stress relaxation characteristics at low-stress levels. Accordingly, relaxation lives against mechanical loading amplitudes under various shot peening intensities were identified and are presented in Fig. 10 together with the cyclic run-out data, which principally are in terms of infinite relaxation lives. Correlation between mechanical stress amplitude with relaxation life of shot peening specimens is modeled by

\[
\frac{\sigma_m^R}{\sigma_b} = r \left( N_R f \right)^s,
\]

where \( r \) and \( s \) are fitting parameters, \( r = 0.53, s = -0.033 \) for \( Q = 0.1 \text{ mmA} \), \( r = 0.552, s = -0.032 \) for \( Q = 0.25 \text{ mmA} \) and \( r = 0.528, s = -0.021 \) for \( Q = 0.4 \text{ mmA}, \) respectively. Therefore, the relaxation life \( N_R f \) is given by

---

**Table 3** Monotonic/cyclic and fatigue parameters of SS304 in the study

| \( \sigma_y \) (MPa) | \( \sigma_{f, \text{fot}} \) (MPa) | \( E \) (GPa) | \( K' \) (MPa) | \( \sigma_{f, \text{fot}} / \sigma_y \) (MPa) |
|-----------------|-----------------|-------------|-------------|-----------------|
| 680 ± 5         | 220 ± 5         | 198 ± 5     | 1660        | 798             |
| \( \psi \)      | \( \delta \)    | \( \nu \)   | \( n' \)    | \( b \)         |
| 0.74 ± 0.2      | 0.94 ± 0.2      | 0.3 ± 0.1   | 0.287       | -0.102          |

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3.3 Characterization of subsequent fatigue failure process of shot peening specimens

The results of the fatigue tests are presented in Fig. 12 in terms of the applied mechanical nominal stress amplitude against the number of cycles to failure, comparing the $S - N$ data for un-peened specimens with 0.1 mmA-/0.25 mmA-/0.4 mmA-peened specimens, respectively. The Morrow’s equation considering the influence of mean stress $\sigma_m$ was introduced to model the relationship between the stress amplitude $\sigma_a$ and fatigue life $N^F_f$ and expressed as

$$\sigma_a = (\sigma'_f - \sigma_m)(2N^F_f)^b$$

where $\sigma'_f$ and $b$ are fatigue strength coefficient and fatigue strength exponent, respectively. The correlation of fatigue
parameters with monotonic tensile parameters to meet the feasibility of engineering structure life prediction is given in [37]. Therefore, the fatigue strength coefficient and fatigue strength exponent were obtained and are presented in Table 3.

Stress amplitude and mean stress in the peening-induced notch root are separately illustrated in Eq. (11),

\[
\begin{align*}
\sigma_a &= \frac{1}{2}(\sigma_{\text{max}}^M - \sigma_{\text{min}}^M), \\
\sigma_m &= \frac{1}{2}(\sigma_{\text{max}}^M + \sigma_{\text{min}}^M),
\end{align*}
\]

where \(\sigma_{\text{max}}^M\) and \(\sigma_{\text{min}}^M\) are maximum/minimum mechanical stress components, respectively, during the fatigue loading process. Since both the stable compressive residual stress \(\sigma_{\text{max}}^R,\) and stress concentration induced by shot peening were considered, \(\sigma_{\text{max}}^M\) and \(\sigma_{\text{min}}^M\) can be further given by

\[
\begin{align*}
\sigma_{\text{max}}^M &= K_i \sigma^M - |\sigma_{\text{max}}^R,\text{stable}|, \\
\sigma_{\text{min}}^M &= -K_i \sigma^M - |\sigma_{\text{max}}^R,\text{stable}|.
\end{align*}
\]

The compatibility of Eqs. (12) and (11) is employed to derive

\[
\begin{align*}
\bar{\sigma}_a &= K_i \sigma^M, \\
\bar{\sigma}_m &= -|\sigma_{\text{max}}^R,\text{stable}|.
\end{align*}
\]

Substituting Eq. (13) into Eq. (10) yields the fatigue life of shot peening specimens as

\[
N_f^F = \frac{1}{2} \left(\frac{\bar{\sigma}_a}{\bar{\sigma}_l - \bar{\sigma}_m}\right)^{\frac{1}{b}}.
\]

Relating Eqs. (4), (9), and (14) finally gives

\[
N_f^T = N_f^R + N_f^F = \left(1 - \frac{\sigma^M}{\sigma_b}\right)^{s} + \frac{1}{2} \left(\frac{\bar{\sigma}_a}{\bar{\sigma}_l - \bar{\sigma}_m}\right)^{\frac{1}{b}},
\]

with \(\sigma_S < \sigma^M < \sigma_b\), which reasonably give the loading possibilities between the fatigue limit \(\sigma_S\) and the ultimate stress \(\sigma_b\).

3.4 A unified model to evaluate fatigue performance of shot peening specimens in extra-low-, low-, and high-cycle regime

Basically, Eq. (15) provides a successfully life prediction of specimens with various peening treatments in a wide life regime, \(10^3\text{-}10^6\). It is, however, essential to provide a fully description of fatigue performance of shot peening specimens, since the life transition phenomenon was identified in extra-low-/low-cycle regime (< \(10^3\)), in which failure lifetime of peened specimens is significantly shorter than that of the un-peened specimens; meanwhile, improvement of fatigue performance was also identified in high-cycle regime (> \(10^6\)), in which fatigue limits of peened specimens are significantly greater than that of the un-peened specimens. In light of this, a closer look at the monotonic tensile test in the perspective of the current investigation suggests that a monotonic tensile process is designated as a quarter of a fatigue cycle [37]. It is, therefore, reasonable to determine the upper limit of the \(S - N\) curve in extra-low cycle regime by taking a constant stress amplitude identical to the ultimate stress. Similarly, the lower limit of the \(S - N\) curve in high-cycle regime can be also determined by introducing the fatigue limits of various shot peening intensities into account. In view of the description of the \(S - N\) curve in the medium cycle regime, namely \(10^3\text{-}10^6\) by Eq. (15) and in accordance with the determination of the upper/lower limits of the \(S - N\) curve in extra-low/high-cycle regime, a unified model to evaluate fatigue performance of shot peening specimens in extra-low-, low-, and high-cycle regime is given by

\[
N_f^T = \begin{cases} 
N_f^{\text{ExL}}(\geq 1/4), & \sigma^M = \sigma_b, \\
N_f^{T}( \frac{1}{r} \frac{\sigma^M}{\sigma_b} )^s + \frac{1}{2} \left(\frac{\bar{\sigma}_a}{\bar{\sigma}_l - \bar{\sigma}_m}\right)^{\frac{1}{b}}, & \sigma_S < \sigma^M < \sigma_b, \\
N_f^{H}, & \sigma^M \leq \sigma_S,
\end{cases}
\]

with \(N_f^{\text{ExL}}\) and \(N_f^{H}\) are fatigue lives in extra-low-/high-cycle regime. Since the fatigue limits of specimens against shot

![Fig. 11 Relationship between shot peening intensities and fatigue limits of SS304](image-url)
peening intensities are illustrated in Fig. 11, which can be well described by a linear relationship

$$\sigma_S = A + B \cdot Q,$$

(17)

with $A=210.6$ and $B=136.7$ are both fitting parameters. Therefore, a comparison of experimental and predicted failure lives of specimens with different shot peening intensities in extra-low-, low-, and high-cycle regime is identified and available in Fig. 12. However, insufficient data about the fatigue tests in extra-low cycle regime conducted were available to construct extremely convincing $S – N$ curves. However, the life transition phenomenon caused by shot peening treatments has also been identified, which is consistent with the indication of the new model.

On the purpose to further clarify the relationship and evolution characteristics of relaxation life component $N_{Rf}$ and fatigue life component $N_{Ff}$ with total failure life component $N_{Tf}$ of specimens machined from SS304 with three

![Fig. 12](image12.png)

*Fig. 12* A comparison of experimental and predicted failure lives of specimens with different shot peening intensities in extra-low-, low-, and high-cycle regime.

![Fig. 13](image13.png)

*Fig. 13* Relationship and evolution characteristics of relaxation life component ($N_{Rf}$), fatigue life component ($N_{Ff}$), and total failure life component ($N_{Tf}$) of specimens machined from SS304 with three shot peening intensities: (a) 0.1 mmA, (b) 0.25 mmA, and (c) 0.4 mmA, respectively.
shot peening intensities, namely 0.1 mmA, 0.25 mmA, and 0.4 mmA, detail illustrations on \( S - N \) curves are shown in Fig. 13. It can be seen in Fig. 13, the blank box and gray box represent relaxation life component and fatigue life component, respectively. Both of the relaxation and fatigue life components can be separately illustrated by a straight line in the \( S - N \) diagram which is a \( \log - \log \) plot of the mechanical stress amplitude against the fatigue cycles. It should be noted that in this paper, ultra-low-cycle fatigue tests were carried out for 0 mmA and 0.4 mmA to verify the life transition phenomenon before and after shot peening. Although the predicted results are more conservative than the test results in this regime, it may be due to the introduction of strengthening behavior of materials under high stress amplitude loading.

Accordingly, both Figs. 12 and 13 present the life prediction results of specimens with different shot peening intensities. In light of this, a master life diagram on evaluating and predicting fatigue performance of shot peening specimens against various shot peening intensities in extra-low-, low-, and high-cycle fatigue life regime for SS304 was developed on purpose of predicting or evaluating the fatigue life and performance of shot peeled structures in service by linear interpolation of shot peening intensities. Although the fatigue tests in this paper are carried out under the condition of \( R = -1 \), the strategy in this paper can also be applied to the fatigue failure assessment of other stress ratios (see Fig. 14).

### 3.5 Correlation of fractography with fatigue performance of shot peening specimens machined from SS304

Typical fracture surfaces of un-peened and peened (0.1 mmA, 0.25 mmA, and 0.4 mmA) specimens were examined by FE-SEM (field emission electric scanning microscopy) technique. Figure 15a–d presents the fracture morphologies of un-, 0.1 mmA-, 0.25 mmA-, and 0.4 mmA-peened specimens subjected to cyclic mechanical load, respectively. Overall and detailed illustrations on fatigue crack initiations (left side, marked with red arrows) and fatigue striations (right side) are shown in Fig. 15. The results indicate that the failure of un-peened/peened specimens is characterized with multiple-fatigue initiations to failure. The characteristics of multi-crack initiation are widely reported in shot peening specimens and components [11, 25, 29, 30, 38, 39]. Generally, shot peening treatments-induced surface roughness not only destroys the surface integrity of the peened specimens, but also introduces a large number of notch characteristics, leading to stress concentration, thereby makes these notches become the hot spot of fatigue failure of shot peened structures. Moreover, with the increase of

![Fig. 14](image-url)
Fig. 15  Typical fracture surface of un-peened and peened (0.1 mmA, 0.25 mmA, and 0.4 mmA) specimens
shot peening intensities, the cross-section size of the peened specimen may also be changed, resulting in the distortion of the structure [31, 32, 40], which leads to the existence of multiple potentially dangerous nominal cross sections of the specimen.

The characteristics of multi-crack initiation are widely found in shot peening specimens and components [11, 25, 29, 30, 38, 39]. Shot peening treatments make the roughness of peened surface increase, which not only destroys the surface integrity of the peened specimens, but also introduces a large number of notch characteristics, leading to stress concentration, and makes these notches become the hot spot of fatigue failure of shot peening structures. Moreover, with the increase of shot peening intensity, the cross-section size of the peened specimen may also be changed, resulting in the distortion of the structure [31, 32], which leads to the existence of multiple potentially dangerous nominal cross sections of the specimen.

Figure 16 extracts the morphology of the crack growth process and further indicates that multi-crack initiation phenomenon may also occur on different cross sections of the peened specimens. Therefore, Figs. 15 and 16 show two types of multi-crack initiation phenomena, respectively, namely multi-crack initiation in the same nominal cross section and multi-crack initiation in different nominal cross section of the peened specimens. Since the total fatigue life of shot peening specimens considered the fatigue crack growth process, the multiple crack initiation phenomena will greatly reduce the crack growth life of shot peening specimens, which makes the predicted life is non-conservative with regard to the test life (Figs. 12 and 13).

Figure 17 gives more detailed analysis on the characteristics of microstructures in the crack initiation position and crack propagation path. With respect to the fatigue crack initiation of the peened specimen subjected to cyclic mechanical loads, fracture collapsed at the anomalies of

![Fig. 16 Morphology of fatigue crack growth process of peened specimens characterized by multi-crack initiation phenomenon](image)

![Fig. 17 Characterization on the microstructures in the crack initiation positions and crack propagation path by EDS probe](image)
the surface/subsurface (Fig. 17a). The red dash circled region indicates one of the cracking initiations, in which the anomaly is highlighted with S3. With the help of EDS probe, chemical composition analysis of S3 confirmed the carbide aggregation which will significantly degrade the fatigue life of shot peened specimens machined from SS304. In Fig. 15, randomly distributed small pits were identified as grain boundary inclusions in the accelerated crack growth stage, which present mostly between grains. Meanwhile, numerous granular inclusions are found in these pits. The detailed characteristics of them observed at higher magnification of microscope are available in Fig. 17b. As presented, these inclusions are small spherical particles with a diameter of ca. 3 µm. The chemical composition of these spherical particles is identified as manganese (Mn) by EDS probe, which is exactly the identity of the strengthening phase element of SS304.

4 Conclusions

In this paper, characterization and modeling on the shot peening process, surface morphology, residual stress relaxation, and fatigue performance of shot peened specimens machined form SS304 were investigated and the following conclusions can be drawn:

- Correlations between shot peening intensities and residual stress distributions and surface morphologies were quantitatively described.
- A life prediction model capable of clarifying the relaxation life component and fatigue life component was developed on evaluating the fatigue performance of shot peening components in extra-low-, low-, and high-cycle regime and acquired satisfied life prediction results for various shot peening intensities.
- The life transition phenomenon was found, which quantitatively clarified that shot peening is not necessarily beneficial to the fatigue life of the structure.
- Characterization of multiple-fatigue initiation to failure of shot peening specimens was identified by fractography analysis, which reasonably illustrated the non-conservative life prediction in high-cycle regime.

Acknowledgements Thanks for the help of Residual Stress Analysis and Shot peening Enhancement Lab (RSA-SP Lab), Shanghai Jiaotong University, in residual stress measurement.

Author contributions Shun YANG contributed to the accessible experimental data analysis, life model establishment, literature review, manuscript writing, and modification. RSA-SP Lab provided the service of residual stress measurement.

Availability of data All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval Herewith the confirmation: The paper was and is not submitted for publication elsewhere. This paper has not been published elsewhere in its entirety, in part, or in a modified version. The paper was not submitted for possible publication elsewhere.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The author declares no competing interests.

References

1. Li H, Zhang W, Wei J, Hua X, Guo X, Fu X, Tao J (2018) The feasibility research on shot-peen forming of the novel fiber metal laminates based on aluminum-lithium alloy. Int J Adv Manuf Technol 96:4039–4053
2. Kulekci M, Esme U (2014) Critical analysis of processes and apparatus for industrial surface peening technologies. Critical analysis of processes and apparatus for industrial surface peening technologies 74:1551–1565
3. Jinu G, Sathiya P, Ravichandran G, Rathinam A (2009) Investigation of the fatigue behaviour of butt-welded joints treated by ultrasonic peening process and compared with fatigue life assessment standards. Int J Adv Manuf Technol 40:74–83
4. Van Bo N, Teo A, Ba T, Aramcharooen A, Ahiuwalia K, Tran S, Kang CW (2021) Advanced model-based controller for cyber-physical shot peening process. Int J Adv Manuf Technol 114:1–15
5. Shen L, Wang L, Wang Y, Wang C (2010) Plasma nitriding of aisi 304 austenitic stainless steel with pre-shot peening. Surf Coat Technol 204(20):3222–3227
6. Lu Z, Shi L, Zhu S, Tang Z, Jiang Y (2015) Effect of high energy shot peening pressure on the stress corrosion cracking of the weld joint of 304 austenitic stainless steel. Mat Sci Eng A 637(18):170–174
7. Bencouia S, Merakbi N, Adjel S, Ehlers S, Baccouche M, Kaddour A (2019) Fatigue life enhancement of tig-welded 304l stainless steels by shot peening. Int J Adv Manuf Technol 100:2885–2893
8. Webster G, Ezeilo A (2001) Residual stress distributions and their influence on fatigue lifetimes. Int J Fatigue 23:375–383
9. Miao HY, Demers D, Larose S, Perron C, Lévesque M (2010) Experimental study of shot peening and stress peen forming. J Mater Process Technol 210(15):2089–2102
10. Dalaei K, Karlsson B (2012) Influence of shot peening on fatigue durability of normalized steel subjected to variable amplitude loading. Int J Fatigue 35:75–85
11. Avilés A, Avilés R, Albizuri J, Pallarés-Santasmartas L, Rodríguez A (2019) Effect of shot-peening and low-plasticity burnishing on the high-cycle fatigue strength of din 3crnim o6 alloy steel. Int J Fatigue 119:338–354
12. Li X, Zhang J, Yang B, Zhang J, Wu M, Lu L (2020) Effect of micro-shot peening, conventional shot peening and their combination on fatigue property of ea4t axle steel. J Mater Process Technol 275:116320
13. Zhu K, Li Z, Fan G, Xu R, Jiang C (2019) Thermal relaxation of residual stress in shot-peened ctn/al-mg-si alloy composites. J Mat Res Tech 8(2):2201–2208
14. Benedetti M, Fontanari V, Bandini M (2014a) A simplified and fast method to predict plain and notch fatigue of shot peened high-strength aluminium alloys under reverse bending. Surface and Coatings Technology 243:2–9
15. Benedetti M, Fontanari V, Bandini M, Taylor D (2014b) Multiaxial fatigue resistance of shot peened high-strength aluminium alloys. Int J Fatigue 61:271–282
16. Benedetti M, Fontanari V, Allahkarami M, Hanan J, Bandini M (2016) On the combination of the critical distance theory with a multiaxial fatigue criterion for predicting the fatigue strength of notched and plain shot-peened parts. Int J Fatigue 93:133–147
17. Bianchetti C, Delbergue D, Bocher P, Lévesque M, Brochu M (2019) Analytical fatigue life prediction of shot peened aa 7050–T451. Int J Fatigue 118:271–281
18. Ferreira N, Jesus J, Ferreira J, Capela C, Costa J, Batista A (2020) Effect of bead characteristics on the fatigue life of shot peen al 7475–T7451 specimens. Int J Fatigue 137:105621
19. Yang S, Zeng W, Yang J (2020) Characterization of shot peening properties and modelling on the fatigue performance of 304 austenitic stainless steel. Int J Fatigue 134:105521
20. Bagherifard S, Ghelichi R, Guagliano M (2012) On the shot peening surface coverage and its assessment by means of finite element simulation: A critical review and some original developments. Appl Surf Sci 259:186–194
21. Lainé SJ, Knowles KM, Doorbar PJ, Cutts RD, Rugg D (2017) Microstructural characterisation of metallic shot peened and laser shock peened ti-6al-4v. Acta Materialia 123:350–361
22. Marini M, Piona F, Fontanari V, Bandini M, Benedetti M (2020) A new challenge in the dem/fem simulation of the shot peening process: The residual stress field at a sharp edge. Int J Mech Sci 169:105327
23. Kim JC, Cheong SK, Noguchi H (2014) A non-microstructural crack formation model for understanding fatigue life degradation in shot peened carbon steel under lcf loading. Int J Fatigue 63:110–117
24. Benedetti M, Fontanari V, Bandini M, Savio E (2015) High- and very high-cycle plain fatigue resistance of shot peened high-strength aluminium alloys: The role of surface morphology. Int J Fatigue 70:451–462
25. Bianchetti C, Lévesque M, Brochu M (2018) Probabilistic analysis of the effect of shot peening on the high and low cycle fatigue behaviors of aa 7050–T451. Int J Fatigue 111:289–298
26. Bag A, Lévesque M, Brochu M (2020) Effect of shot peening on short crack propagation in 300m steel. Int J Fatigue 131:105346
27. Eriksson R, Moverare J, Chen Z (2019) A low cycle fatigue life model for a shot peened gas turbine disc alloy. Int J Fatigue 124:34–41
28. Walker J, Thomas DJ, Gao Y (2017) Effects of shot peening and pre-strain on the fatigue life of dual phase martensitic and bainitic steels. J Manuf Process 26:419–424
29. Zhao X, Zhou H, Liu Y (2018) Effect of shot peening on the fatigue properties of nickel-based superalloy gb4169 at high temperature. Results in Physics 11:452–460
30. Amanov A, Karimbaev R, Maleki E, Unal O, Pyun YS, Amanov T (2019) Effect of combined shot peening and ultrasonic nanocrystal surface modification processes on the fatigue performance of aisi 304. Surf Coat Technol 358:695–705
31. Klotz T, Lévesque M, Brochu M (2018) Effects of rolled edges on the fatigue life of shot peened inconel 718. J Mater Process Technol 263:276–284
32. Persenot T, Burr A, Plancher E, Buffière JY, Dendievel R, Martin G (2019) Effect of ultrasonic shot peening on the surface defects of thin struts built by electron beam melting: Consequences on fatigue resistance. Addit Manuf 28:821–830
33. Li JK, Mei Y, Duo W, Renzhi W (1992) An analysis of stress concentrations caused by shot peening and its application in predicting fatigue strength. Fatigue & Fracture of Engineering Materials & Structures 15(12):1271–1279
34. Clausen R, Stangenberg J (1999) Roughness of shot peened surfaces definition and measurement. Proc 7th Conf Shot Peening (ICSP7) pp 69–77
35. Rodopoulos C, Curtis S, de los Rios E, Solis-Romero J (2004) Optimisation of the fatigue resistance of 2024–t351 aluminium alloys by controlled shot peening-methodology, results and analysis. Int J Fatigue 26(8):849–856
36. Jie F (2015) Cyclic plasticity modeling and multiaxial fatigue assessment for an austenitic steel. Herbert Utz Verlag
37. Yang S, Yang L, Wang Y (2020) Determining the fatigue parameters in total strain life equation of a material based on monotonic tensile mechanical properties. Eng Fract Mech 226:106866
38. Zhou J, Retraint D, Sun Z, Kanouté P (2018) Comparative study of the effects of surface mechanical attrition treatment and conventional shot peening on low cycle fatigue of a 316l stainless steel. Surf Coat Technol 349:556–566
39. Wu D, Yao C, Zhang D (2018) Surface characterization and fatigue evaluation in gb4169 superalloy : Comparing results after finish turning; shot peening and surface polishing treatments. Int J Fatigue 113:222–235
40. Wang C, Li W, Jiang J, Chao X, Zeng W, Yang J (2021) Mechanical behavior study of asymmetric deformation in double-sided symmetrical sequential shot peening process. Int J Adv Manuf Technol 114:1189–1204

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