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Effects of loading frequency on fatigue behavior of metallic materials—A literature review

Youshi Hong[1] | **Yuanpei Hu**[2] | **Aiguo Zhao**[3]

[1]LNM, Institute of Mechanics, Chinese Academy of Sciences, Beijing, China
[2]Gree Electric Appliances, Inc., Zhuhai, China
[3]College of Civil Engineering, Nanjing Tech University, Nanjing, China

Correspondence
Youshi Hong, LNM, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China.
Email: hongys@imech.ac.cn

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Abstract
The topic of loading frequency effect on fatigue behavior is in close relation to high-cycle fatigue (HCF) and very-HCF (VHCF) research. The conventional loading frequency in fatigue tests is normally between 10 and 100 Hz. In order to accelerate testing process, researchers have developed ultrasonic vibration device with a very high frequency, for example, 20 kHz, to perform VHCF tests. Thus, a question has always been asked: Does loading frequency affect the fatigue behavior of tested material? It is obvious that the answer is yes because the remarkable difference in strain rate with respect to different loading frequencies may cause the change of fatigue mechanism and the related fatigue performance. The subsequent question is how is the effect of loading frequency on fatigue behavior? This paper attempts to address such questions by two cases of experimental investigations. Moreover, typical results in literature are quoted for the further discussion of this issue.

KEYWORDS
fatigue strength, loading frequency, metallic materials, strain rate, very-high-cycle fatigue

Highlights

- Literature review of loading frequency effect on fatigue performance of materials.
- Ultrasonic frequency resulting in higher fatigue strength for low-strength materials.
- Loading frequency effect diminishing for high-strength materials.
- Frequency effect in relation to material's lattice type and specimen temperature rise.

1 | INTRODUCTION

Fatigue testing is under a value of loading frequency that is a key issue in fatigue research history and the development of loading frequency in fatigue testing is briefly described in the following. In 1911, Hopkinson[1] developed a machine with the frequency of about 120 Hz for fatigue testing, before which the highest loading frequency seemed not more than 33 Hz. In 1925, Jenkin[2] reported the fatigue tests on the thin rods (ϕ2.6 mm) made of copper, Armco iron, and mild steel at the frequency up to 2 kHz. In 1929, Jenkin and Lehmann[3] used the frequency of 10 kHz to perform fatigue tests on copper, carbon steel, Armco iron, and aluminum specimens. In early 1950s, Mason[4] was the first to develop the testing device with an ultrasonic frequency of 20 kHz by means of magnetostrictive and piezoelectric transducers. In 1959, Neppiras[5] used ultrasonic frequency to obtain the S–N curves of brass and other materials. Also in 1959, Girard and Vidal[6] reported the fatigue testing at a frequency as high as 92 kHz. In 1965, Kikukawa et al.[7] developed a new resonant type machine by using a magnetostrictive vibrator, and performed fatigue testing at a frequency up to 100 kHz. Their tests on two carbon steels up to 10^9 cycles at the frequencies between 40 Hz and 100 kHz showed the fatigue limit increased with the increasing of loading frequency, which was the first research regarding the loading frequency effect on the fatigue behavior of metallic materials. In 1980, Willertz published a review article[8] summarizing the development process of ultrasonic fatigue research from the early time to 1970s. In 1981, the First International Conference on Fatigue and Corrosion Fatigue up to Ultrasonic Frequencies was held in Pennsylvania and the Proceedings of Ultrasonic Fatigue containing 40 papers was published.[9] Since 1980, the use of ultrasonic frequency, for example, 20 kHz has gradually become a common method in fatigue testing especially in VHCF research. Here, we plot a brief timeline of Figure 1 to show the historical development of loading frequency in fatigue testing in last century. In addition to the one by Willertz,[8] other review articles[10–16] are available in the literature.

Compared with conventional testing frequency (normally between 10 and 100 Hz), ultrasonic frequency (e.g., 20 kHz) is about three orders of magnitude higher than the conventional one. Thus, a question has always been asked: Does ultrasonic frequency cause the change of fatigue property or does loading frequency affect the fatigue behavior of tested material? If the answer is "yes," the follow-up question is: How is the effect of loading frequency on fatigue behavior especially in high-cycle fatigue (HCF) and very-HCF (VHCF) regimes? This paper attempts to address such questions by two cases of previous experimental investigations. In addition, typical results from the literature are reviewed to show how the effects of loading frequency on the fatigue behavior of metallic materials.

Although several review articles[8,10–16] with regard to the topic of loading frequency effect on the fatigue performance of metallic materials have been published, this review article more comprehensively emphasizes the following three aspects: (1) the early research cases and the historical development of loading frequency effect, (2) systematic descriptions of loading frequency effects for body-centered cubic (bcc), hexagonal close-packed (hcp), and face-centered cubic (fcc) lattice type materials, and

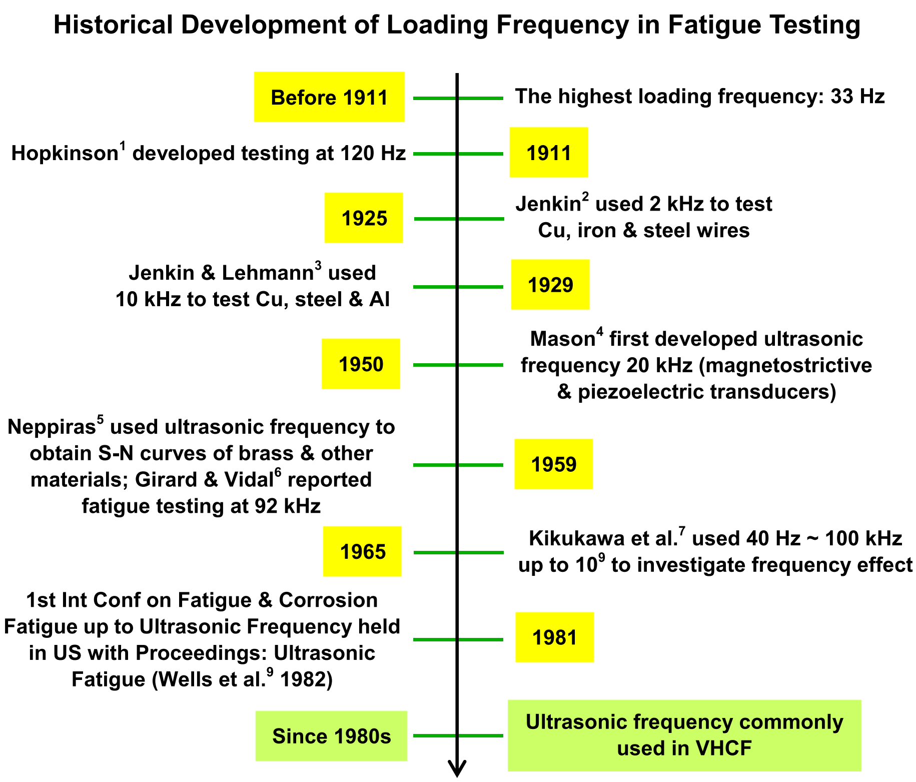

FIGURE 1 Brief timeline showing the historical development of loading frequency in fatigue testing. [Colour figure can be viewed at wileyonlinelibrary.com]

(3) detailed discussion of the roles of strain rate, microstructure lattice type, temperature rise, and the strength state of materials in the impact of loading frequency effect. Thus, this review article provides new insights about the loading frequency effect for the researchers in the community.

2 | CASE I: LOADING FREQUENCY EFFECT EXPLAINED BY DISLOCATION MOVEMENT

2.1 | Test material and specimen

The material tested in this case is a high-strength steel of GCr15 (equivalent SUJ2 or SAE 52100 or NF 100C6) with the main chemical composition (wt %) of 1.01 C, 1.45 Cr and balance Fe. The specimens were austenitized at 845°C and oil quenched. The quenched specimens were divided into four groups (A-1, A-2, A-3, and A-4), which were subjected to tempering treatment for 2.5 h at 150°C, 300°C, 450°C, and 600°C, respectively. The tensile strength for the four groups of specimens are 2372, 2150, 1677, and 1044 MPa, respectively.[17]

2.2 | Fatigue tests and results

Figure 2 shows the schematic of specimens for rotary bending (RB) and ultrasonic cycling. Fatigue tests up to VHCF regime were carried out at conventional frequency (RB, 52.5 Hz) and at ultrasonic frequency (20 kHz), and the latter was with a resonance interval of 100 ms per 500 ms. Both types of tests were in air, at room temperature, and under the stress ratio of $R = -1$.

The obtained S–N data showed that for the groups with high tensile strength of A-1 (Figure 3A) and A-2 (Figure 3B), the values of fatigue strength under conventional frequency and ultrasonic frequency are of little difference, although for A-1, the fatigue strength by RB is somewhat higher than that by ultrasonic cycling, and for A-2, the fatigue strength by RB is somewhat lower than that by ultrasonic cycling. However, for the groups with relatively low tensile strength of A-3 (Figure 3C) and A-4 (Figure 3D), the difference in S–N data under two loading frequencies is remarkable with the fatigue strength by ultrasonic frequency evidently higher than that by conventional frequency.

2.3 | Explanation of frequency effect on fatigue strength in terms of dislocation movement

The fatigue results showed that the effect of loading frequency on fatigue performance is in relation to the strength of material, which is explained in terms of dislocation movement. On one hand, the dislocation movement distance L is inversely related to loading frequency f, that is[17,18]

$$L \propto 1/f \tag{1}$$

On the other hand, the high-strength state of material contains more obstacles against dislocation movement. Thus, the possible damage per cycle under ultrasonic frequency is much smaller than that under conventional frequency especially for the material with low-strength, which is sketched in Figure 4. For the specimens with the highest tensile strength (A-1, 2372 MPa), the density of carbon atoms (regarded as defects) is high, and the interval between obstacles is small. As a result, the dislocation movement distance under different frequencies is almost the same, and the difference in fatigue strength is small, that is, the damage per cycle at 20 kHz and at 52.5 Hz is of little difference as

$$\left.\frac{\text{Damage}}{\text{cyc}}\right|_{20\ \text{kHz}} \approx \left.\frac{\text{Damage}}{\text{cyc}}\right|_{52.5\ \text{Hz}} \tag{2}$$

Therefore, the fatigue strength is of little difference at 20 kHz and 52.5 Hz, as shown typically in Figure 3A.

For the specimens with low tensile strength (A-3, 1677 MPa and A-4, 1044 MPa), the dislocation moving distance under ultrasonic loading is much smaller than

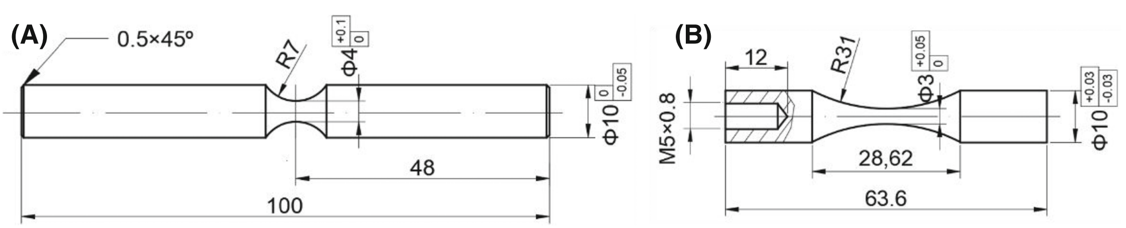

FIGURE 2 Shape and dimensions (mm) of specimens for rotary bending (A) and ultrasonic cycling (B).[17]

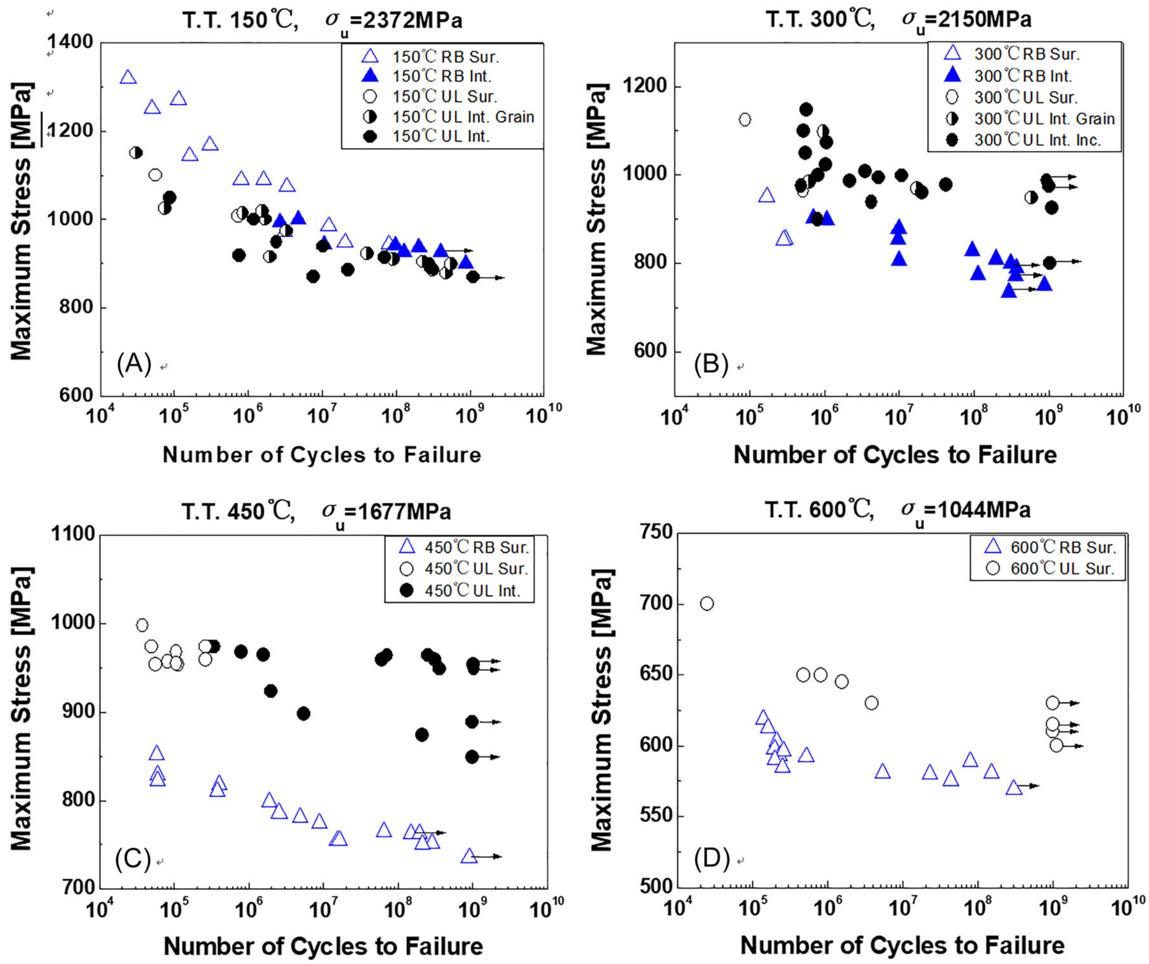

FIGURE 3 S–N data of four test groups: (A) Group A-1, (B) Group A-2, (C) group A-3, and (D) Group A-4.[17] [Colour figure can be viewed at wileyonlinelibrary.com]

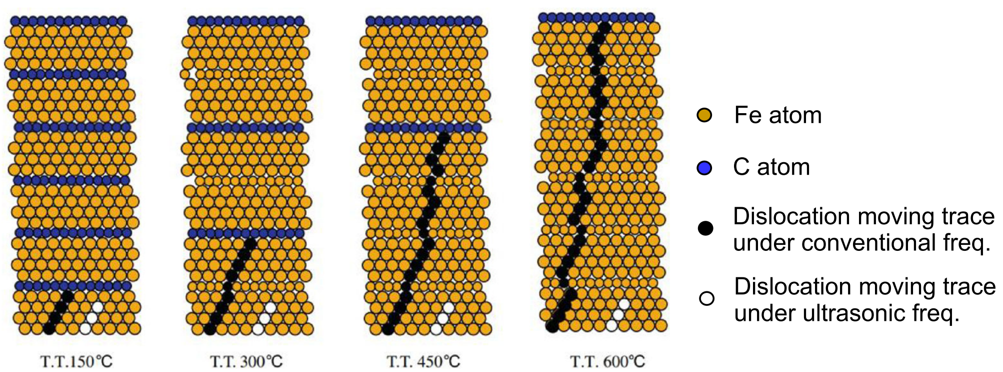

FIGURE 4 Schematic of dislocation movement under different frequencies for different strength states of material.[17] [Colour figure can be viewed at wileyonlinelibrary.com]

that under RB, and thus, the damage per cycle at 20 kHz is remarkably smaller than that at 52.5 Hz, that is

$$\left.\frac{\text{Damage}}{\text{cyc}}\right|_{20\ \text{kHz}} < \left.\frac{\text{Damage}}{\text{cyc}}\right|_{52.5\ \text{Hz}} \tag{3}$$

Therefore, the fatigue strength is evidently higher under ultrasonic cycling as shown in Figure 3C,D.

Here it is summarized that the loading frequency effect on fatigue performance is dependent on the strength of the tested materials. For the case of low-strength state, the effect of frequency effect on fatigue performance is remarkable with the fatigue strength by ultrasonic frequency higher than that by conventional frequency whereas for the case of high-strength state, the effect of frequency effect on fatigue performance is insignificant.

3 | CASE II: LOADING FREQUENCY EFFECT EXPLAINED BY JOHNSON–COOK MODEL

3.1 | Test material and specimen

The material tested in Case II is the same brand of high-strength steel GCr15 as that in Case I and the main chemical composition (wt %) is 1.00 C, 1.52 Cr, and balance Fe. The specimens were austenitized at 845°C and then oil quenched. The quenched specimens were divided into three groups (B-1, B-2, and B-3), which were subjected to tempering treatment for 2 h at 150°C, 200°C, and 400°C, respectively. The tensile strength for the three groups of specimens are 2497, 2425, and 1718 MPa, respectively.[19]

3.2 | Fatigue tests, high strain rate monotonic tests and results

Fatigue tests up to VHCF regime were performed with three types of cycling modes, namely RB at 52.5 Hz, electromagnetic resonance axial loading (EA) at 120 Hz and ultrasonic axial loading (UA) at 20 kHz, respectively. All fatigue tests were in air, at room temperature and with the stress ratio of $R = -1$. RB and UA specimens are the same as shown in Figure 2A,B, and EA specimen is shown in Figure 5. For the ultrasonic axial cycling, the tests were performed with compressed air cooling (UA) and without cooling (UA-NC) on specimen surface for comparison.

The obtained S–N data are shown in Figure 6A,C,E. For the two high-strength states of B-1 and B-2 (Figure 6A,C), the fatigue strength by RB is higher than that by EA and UA, and the data by UA-NC are lower than those by other three methods. For the low-strength state of B-3 (Figure 6E), the fatigue strength by RB is almost the same with that by EA, the fatigue strength by UA and UA-NC is higher than that by EA and RB, and the fatigue strength by UA is higher than that by UA-NC.

In addition, the mechanical properties of the specimens at high strain rate were tested with a separated Hopkinson pressure bar at different temperatures. The results of monotonic mechanical tests under the strain rates of 10^{-4} s^{-1}, 5×10^{-3} s^{-1}, and 500 s^{-1} at 20°C, and under 500 s^{-1} at 100°C and 200°C are shown in Figure 6B,D,F for B-1, B-2, and B-3, respectively, which show that the ultimate strength increases with strain rate at room temperature and decreases with temperature at 500 s^{-1}. The results also indicate that during fatigue testing, the cyclic hardening of the specimen will happen especially at room temperature, and as the temperature increases from 20°C to 200°C, the cyclic hardening extent will be gradually suppressed. For the fatigue testing under EA and UA, the strain rate was between 2 s^{-1} and 4 s^{-1} for EA and between 300 s^{-1} and 700 s^{-1} for UA. It is obvious that the values of ultimate strength of the tested material at 2–4 s^{-1} and 300–700 s^{-1} are higher than that at quasi-static condition (10^{-4} s^{-1}). Thus, it is reasonable to use the material strength at relevant strain rate and temperature in the evaluation of fatigue strength for EA and UA specimens.

An additional set of specimens were used for the temperature detection and measurement to obtain the data of temperature rise for the three groups of specimens. In such tests, a thermocouple was attached to the minimum cross-sectional surface of EA, UA, and UA-NC specimens to monitor the temperature value. Figure 7A shows the average temperature rise at the temperature stable stage as a function of loading stress. The average temperature rise for UA-NC specimens increases rapidly with the value between 80°C and 130°C for B-1 and between 70°C and 110°C for B-2 and B-3 at the loading stress from 450 to 600 MPa. For UA specimens, the temperature rise is less than 50°C at the stress below 800 MPa. Figure 7B shows the temperature rise versus the maximum stress of EA. The temperature rise also increases with loading stress, but the increment is less than 3°C for all three groups, so the effect of temperature rise on the fatigue performance for EA specimens is negligible.

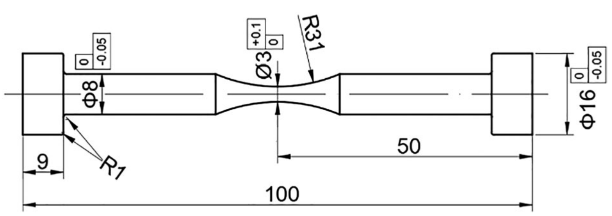

FIGURE 5 Shape and dimensions (mm) of EA specimen.[19]

3.3 | Explanation of frequency effect on fatigue strength by Johnson-Cook model

The Johnson–Cook formula[20] of Equation (4) was used to evaluate the loading frequency effect:

$$\sigma = (A + B\varepsilon^n)(1 + C\ln(\mathrm{d}\varepsilon/\mathrm{d}t)^*)(1 - T^{*m}) \tag{4}$$

where ε is equivalent plastic strain, $(\mathrm{d}\varepsilon/\mathrm{d}t)^* = (\mathrm{d}\varepsilon/\mathrm{d}t)/(\mathrm{d}\varepsilon/\mathrm{d}t)_0$ is dimensionless plastic strain rate for $(\mathrm{d}\varepsilon/\mathrm{d}t)_0 = 1$ s^{-1}, and $T^* = (T - T_r)/(T_m - T_r)$ is homologous temperature with T being experimental temperature, T_r room temperature, and T_m melting temperature

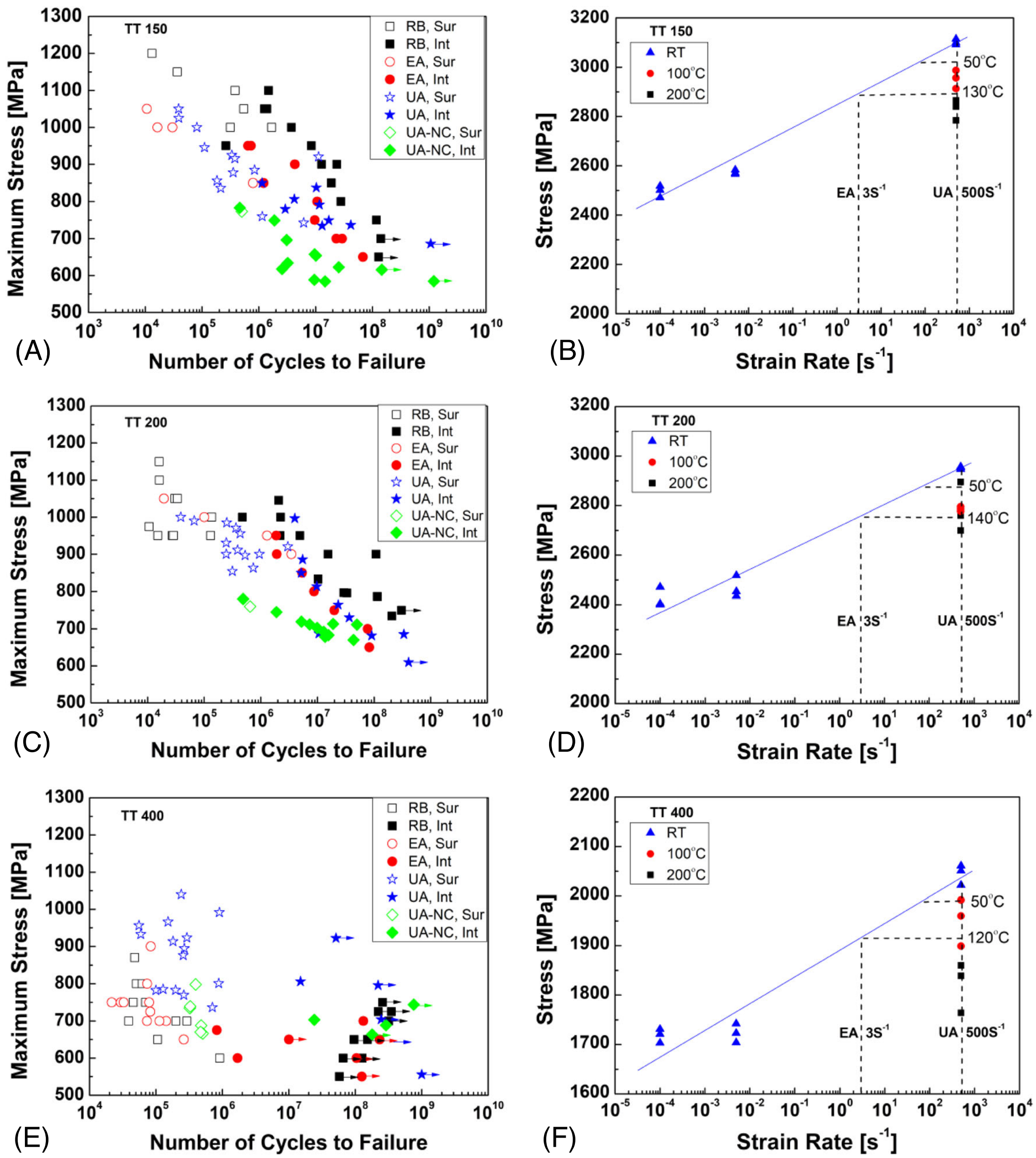

FIGURE 6 S–N data for B-1 (A), B-2 (C), and B-3 (E), (Sur: surface crack initiation, Int: internal crack initiation, symbol with arrow: no broken); and ultimate stress under different loading strain rates and temperatures for B-1 (B), B-2 (D) and B-3 (F), (RT: room temperature).[19] [Colour figure can be viewed at wileyonlinelibrary.com]

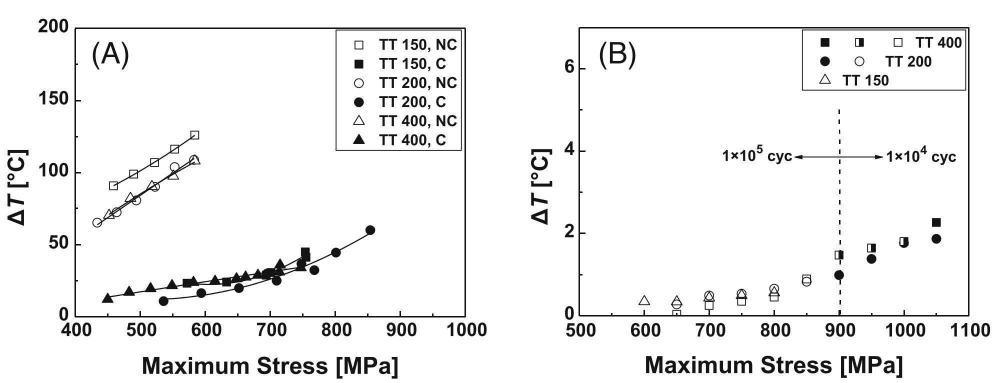

FIGURE 7 Average temperature rise for UA specimens (A) and for EA specimens (B).[19]

of the material. A, B, C, m, and n are material coefficients. The terms in the second and the third brackets represent the effect of strain rate and temperature, respectively. Here, we define a parameter η as the ratio of fatigue strength at ultrasonic (UL) frequency to conventional (CL) frequency, as expressed as Equation (5)[19]:

$$\eta = \frac{\sigma_{\mathrm{UL}}}{\sigma_{\mathrm{CL}}} = \frac{\left(1 + C\ln(\mathrm{d}\varepsilon/\mathrm{d}t)^{*}_{\mathrm{UL}}\right)\left(1 - T^{*m}_{\mathrm{UL}}\right)}{\left(1 + C\ln(\mathrm{d}\varepsilon/\mathrm{d}t)^{*}_{\mathrm{CL}}\right)\left(1 - T^{*m}_{\mathrm{CL}}\right)} \tag{5}$$

The values of η were calculated via Equation (5) with the measured temperature value and the related strain rate as well as the material coefficients. The calculated value of η is used to judge or predict the trend of loading frequency effect. The critical value of η is one. When η is larger than unity, the fatigue strength at UL frequency is higher than that at CL frequency, which means the effect of loading frequency is noticeable, whereas when η is equal or close to unity, the fatigue strength at UL frequency tends to be almost identical with that at CL frequency, which means that the effect of loading frequency is vanishing. It should be noted that Johnson–Cook formula is a kind of constitutive equation indicating the relation between stress and strain as well as strain rate under different temperatures, and the parameter η is the comparison of the resulted stress defined by Johnson–Cook formula, from two fatigue processes with two loading frequencies.

Based on the experimental data, the values of η from Equation (5) for UA and EA specimens (at about 700 MPa) in VHCF regime are obtained. The calculated values of η are all above unity (B-1: 1.103, B-2: 1.108, and B-3: 1.080), indicating the existence of loading frequency effect for the three groups under corresponding low stress. Similarly, the values of η calculated by Equation (5) of UA and UA-NC specimens (at about 585 MPa) are obtained. The values of η are all beyond unity (B-1: 1.134, B-2: 1.107, and B-3: 1.106), indicating that the fatigue strength of UA specimens is higher than that of UA-NC specimens because of the temperature rise of UA-NC specimens. The calculated results are consistent with the trend of S–N data shown in Figure 6.

Therefore, it is summarized that the loading frequency effect can be ascribed to the joint factors of strain rate and temperature rise, and the parameter η based on the Johnson–Cook model is an approach to evaluate the status of loading frequency effect caused by strain rate and temperature variations. Here, it is worthwhile to emphasize that the temperature rise of the specimen induced by high loading frequency will result in the changes of the strength of tested material and therefore result in the degradation of the related fatigue performance.

4 | OTHER TYPICAL CASES FROM LITERATURE

4.1 | The earliest contributions

It is likely that Jenkin[2] was the earliest researcher to perform fatigue tests under a frequency from 50 Hz to 2 kHz to investigate the effect of loading frequency on the fatigue limit of metallic materials about a century ago. Figure 8, as he called as "graphs," is a part of his fatigue test results. He plotted the value of applied strain as a function of failure cycles to give the fatigue resistance (Figure 8A). His results showed that for copper test pieces,[2] the fatigue limit at 2 kHz was 33.7×10^{-8} and

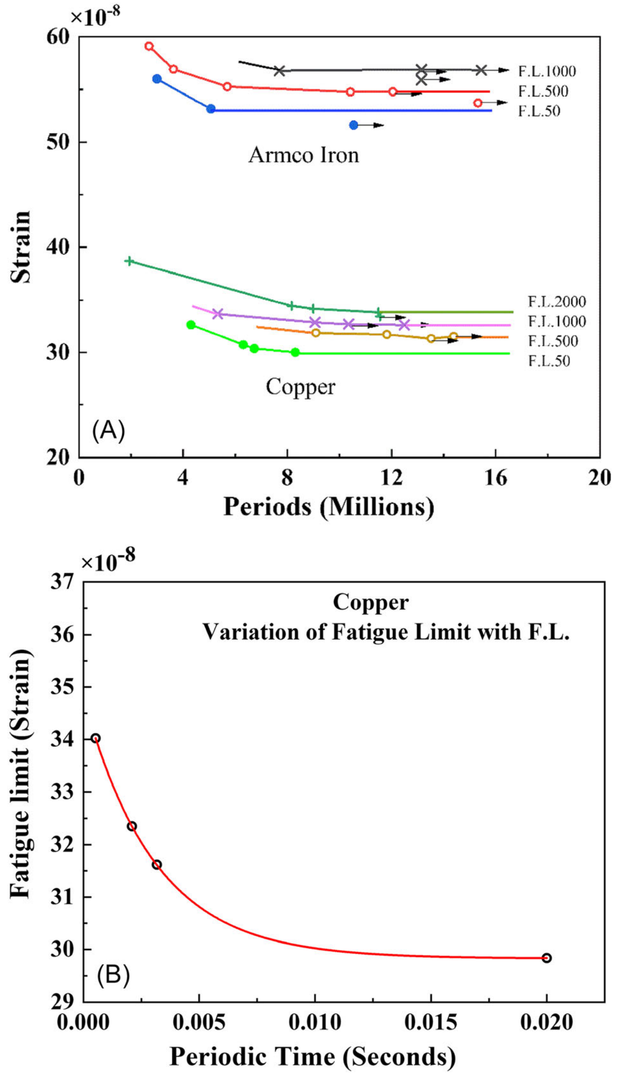

FIGURE 8 (A) Applied strain as a function of failure cycles for Armco iron and copper at different loading frequencies, and (B) fatigue limit as a function of loading frequency for copper (F.L. being loading frequency, reproduced from Jenkin.[2]). [Colour figure can be viewed at wileyonlinelibrary.com]

that at 50 Hz was 29.8 × 10^{-8}, with an increase of 13.1% of the former compared to the latter (Figure 8B). For Armco iron and mild steel test pieces,[2] the loading frequency was between 50 Hz and 1 kHz, and the fatigue limit increase from low to high frequency was 7.8% and 6.3%, respectively. To explore the mechanism of fatigue limit increase at high frequency, Jenkin[2] measured the temperature change of test pieces during high-frequency cycling and for copper the value was less than 8°C, which could have little effect on the fatigue limit. Then he argued that at high loading frequencies the loads that were sufficient to cause fracture had not enough time to produce the effect, and higher loads were needed to produce the same effect. He summarized that any theory proposed to explain the mechanism of loading frequency effect must account for this time effect.

Some years later, Jenkin and Lehmann[3] performed another set of tests with regard to the loading frequency effect on the fatigue performance of metallic materials, and reported that for a high carbon steel the fatigue limit at 1 kHz was higher than that at 50 Hz by 65%.

Another typical example of the earliest results is the work by Kikukawa et al.[7] in 1965. They used the frequency from 40 Hz to 100 kHz to investigate the effect of loading frequency on the fatigue strength of mild steels, and the number of loading cycles was up to 10^9. They reported that higher loading frequency resulted in higher fatigue strength as shown in Figures 9A and 10A for S10C steel and Figures 9B and 10B for S20C steel. They concluded that the fatigue limits of the two tested steels increased monotonically with increasing frequency up to 100 kHz, and no peak was observed in the fatigue limit against frequency relations. It is likely that this is the first result to show the frequency effect up to 10^9 loading cycles.

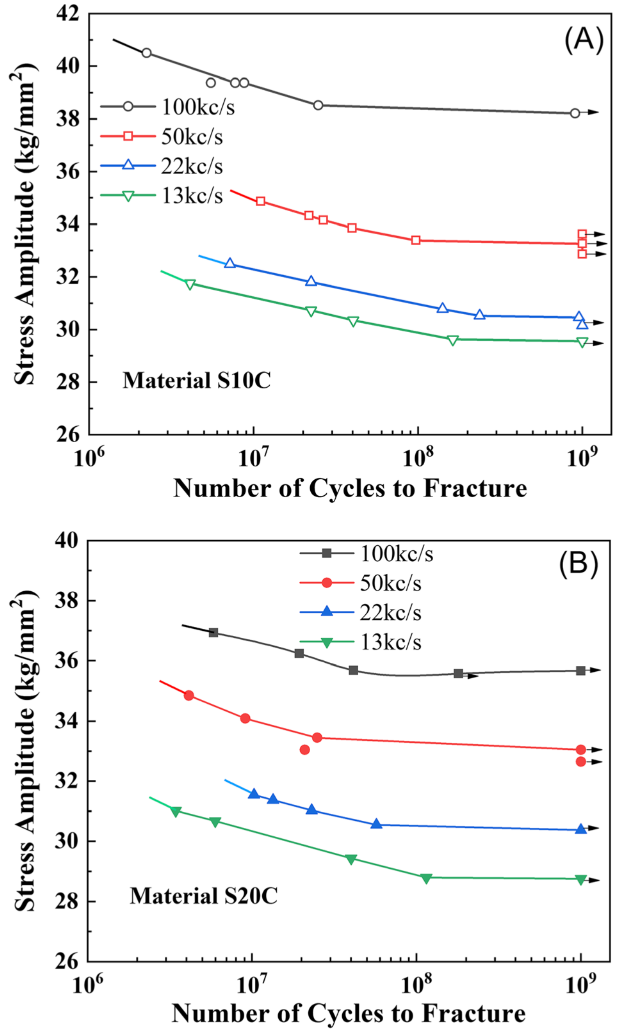

FIGURE 9 S–N data at loading frequency from 13 to 100 kHz, showing higher frequency resulting in higher fatigue strength for S10C steel (A) and S20C steel (B) (reproduced from Kikukawa et al.[7]). [Colour figure can be viewed at wileyonlinelibrary.com]

4.2 | Propensities of bcc materials

In general, the loading frequency effect on the fatigue behavior of metallic materials is evident for bcc lattice. This is mainly because that the feature of slip systems for bcc crystals is of relatively small atomic plane spacing and large atomic distance, and therefore the Peierls–Nabarro stress to activate dislocation movement is relatively high,[21] which will be further addressed in Section 5. The previous case of mild steels that contain basically bcc α phase demonstrates the fact of higher frequency resulting in higher fatigue strength under the cycling from 40 Hz to 100 kHz (Figures 9 and 10).

Figure 11[22] is another example of bcc metal Tantalum (Ta) showing the evident loading frequency effect on fatigue performance, with ultrasonic frequency (20 kHz) resulting in higher fatigue strength than that by conventional frequency (100 Hz), although the loading type of the former is axial cycling and that of the latter is RB (with the stress ratio of −1 for both tests). Note that in ultrasonic fatigue tests, a pulse-pause loading mode was adopted along with a forced air cooling to ensure the temperature rise of tested specimens being negligible. For the annealing state of commercially pure (c.p.) Ta, the fatigue limits are 335 MPa under 20 kHz and 270 MPa under 100 Hz (Figure 11A), with an increase of 24.1% by ultrasonic frequency. For the cold working state of c.p. Ta, the value of fatigue limit under 20 kHz is 365 MPa, and that under 100 Hz is 290 MPa, with an increase of 25.9% by ultrasonic frequency (Figure 11B). It also shows that the fatigue performance of the cold working state with the tensile strength of 316 MPa (yield strength 300 MPa) is a bit better than that of the

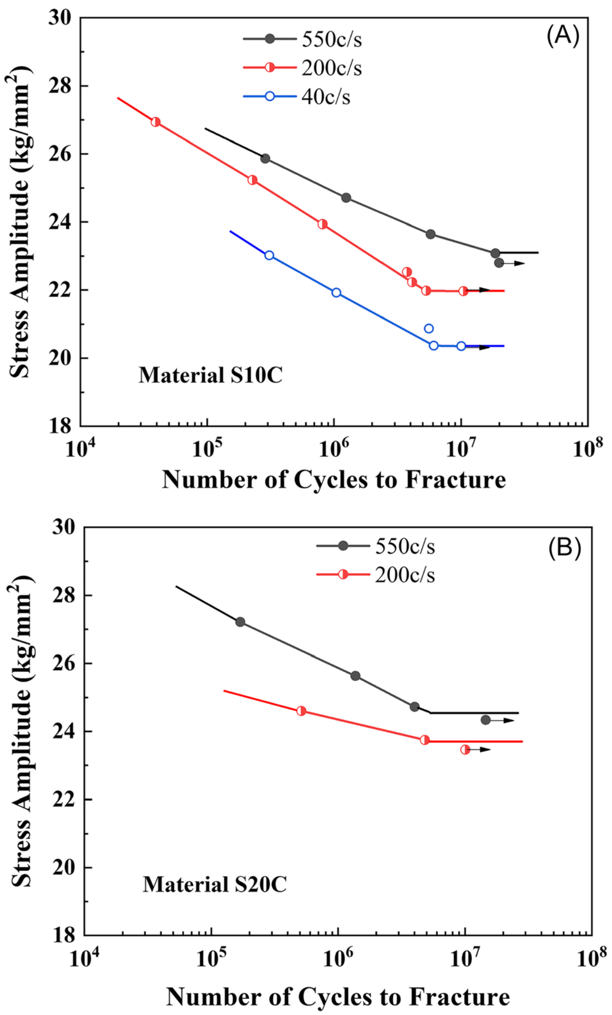

FIGURE 10 S–N data at loading frequency from 40 to 550 Hz for S10C steel (A) and from 200 to 550 Hz for S20C steel (B), showing higher frequency resulting in higher fatigue strength (reproduced from Kikukawa et al.[7]). [Colour figure can be viewed at wileyonlinelibrary.com]

annealing state with the tensile strength of 283 MPa (yield strength 234 MPa). Note that the values of fatigue limit in this case are higher than the static strength of this material. For this, Papakyriacou et al.[22] explained that cyclic hardening increases the yield stress of tantalum and high plastic strain amplitudes at the beginning of a fatigue test may have caused the frequency sensitive fatigue damage of this bcc metal. Papakyriacou et al.[22] also argued that the strain rate dependent flow stress and the asymmetric slip of screw dislocations in bcc crystals may explain the observed frequency effects in the high-cycle and very-high-cycle regimes.

Figure 12 is one more example of bcc material by Guennec et al.[23] showing the effects of loading frequency on the fatigue strength of a low carbon structure steel S15C (0.15%C) with the yield strength of 273 MPa and the tensile strength of 441 MPa. The fatigue tests were conducted by ultrasonic cycling at 20 kHz with pulse-pause (110-ms loading and 2500-ms rest time) sequence plus air cooling, electro-magnetic type at 140 Hz with air cooling, and servo-hydraulic type at 20, 2, and 0.2 Hz. All tests were axial mode in air at room temperature with the stress ratio of $R = -1$. The test results of Figure 12 illustrate remarkable loading frequency effect on the fatigue strength of the tested material. The fatigue strength/limit under ultrasonic frequency is much higher than that under conventional frequencies, and the value of fatigue limit increases with the increase of loading frequency: 178 MPa for 0.2 Hz, 187 MPa for 2 Hz, 192 MPa for 20 Hz, 200 MPa for 140 Hz, and 248 MPa for 20 kHz. Guennec et al.[23] explained that in the conventional frequency ranging from 0.2 to 140 Hz, the loading frequency dependence is caused by the effect of the strain rate on the yield stress, whereas in the case of ultrasonic frequency at 20 kHz, the loading frequency effect is

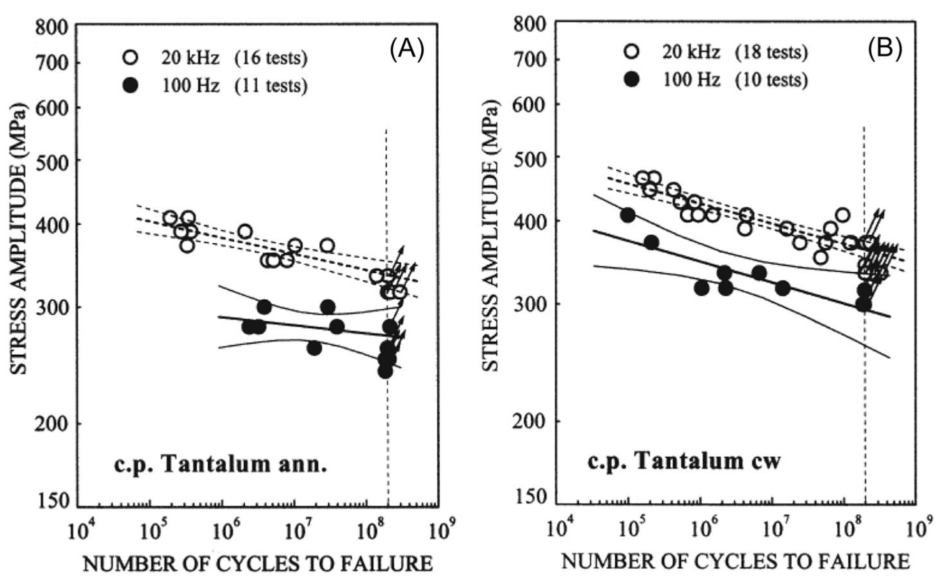

FIGURE 11 S–N data of commercially pure (c.p.) Ta with annealing state (A) and with cold working state (B); thick lines indicating 50% probability of survival and thin lines denoting 95% confidence intervals; arrows indicating run-out specimens.[22]

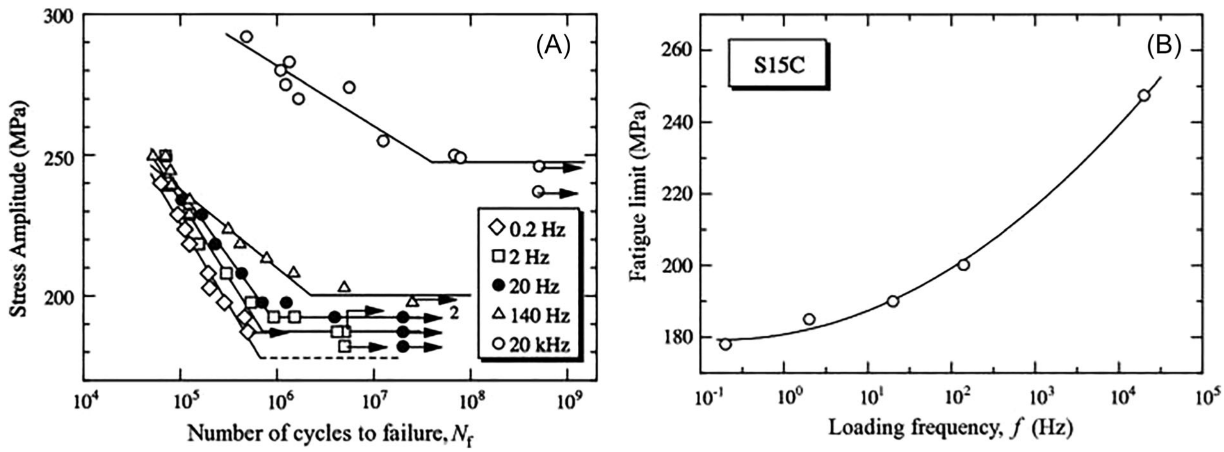

FIGURE 12 Fatigue strength increasing with loading frequencies from 0.2 Hz to 20 kHz of S15C steel, (A) S–N data, and (B) fatigue limit.[23]

probably due to the local mis-orientation of crystal lattice in addition to the strain rate effect on the yield stress of the tested bcc material.

Figure 13A[24] is a further example of bcc type material of welded joints made of 25Cr2Ni2MoV steel with the tensile strength of 778 MPa for weld part and that of 864 MPa for base metal. The fatigue tests were under ultrasonic vibration at 20 kHz and electro-magnetic type resonant at 110 Hz. For the resonant cycling, no cooling measures on the tested specimen were taken. For ultrasonic vibration at 20 kHz, compressive air was used in addition to the pulse-pause loading process (500-ms pulse followed by 1000-ms pause) to minimize the temperature rise of tested specimen. The results of Figure 13A illustrates that the fatigue strength at 20 kHz is much higher than that at 110 Hz, indicating a significant influence of loading frequency on the fatigue strength of the welded joints, and the difference in fatigue strength caused by the two frequencies is larger in VHCF compared with HCF regime. To explain the results of such frequency effect, Zhu et al.[24] stated that the strain-rate sensitivity is more obvious in the material with bcc crystal structure due to fewer slip systems remaining active at higher frequency, hence requiring higher activation energy for dislocation movement.

Figure 13B[25] is an interesting example of bcc type steel of SCM440 (AISI-4140), with the results showing that the values of fatigue strength by ultrasonic testing at 20 kHz are almost the same as that by servohydraulic testing at 20 Hz. The tested material was quenched from 1153 K and tempered at 473 K to give the Vickers hardness of HV604, which was quite high and could be equivalent to the tensile strength of about 1900 MPa.[26] In the ultrasonic testing at 20 kHz, the specimens were air-cooled and subjected to an intermittent loading mode to keep the specimen surface below 303 K, and both tests were at the stress ratio of $R = -1$. Furuya[25] paid special attention to the value of control volume of the specimens, and the value for the ultrasonic fatigue specimen (ϕ8 × 10 mm) is almost equal to that of servohydraulic fatigue specimen (ϕ6 × 14 mm). Note that the control volume is defined as the volume of bearing ≥90% of the maximum loading stress.[27] Therefore, Furuya[25] concluded that the ultrasonic fatigue testing results showed good agreement with conventional servohydraulic testing results by using equal control volume of the specimens. Thus, it is interesting that the loading frequency effect is almost vanishing for this case of a bcc material with the high value of tensile strength and with the equal value of specimen control volume in ultrasonic and conventional frequency tests.

Figure 14 is a very recent case reporting the loading frequency effect on the fatigue strength for a bcc material of structural steel S355 with two grades of S355J0 and S355J2.[28] The values of tensile strength for these two grades are 508 and 555 MPa, respectively, with J2 grade about 9% higher than J0 grade. The servohydraulic testing was at a loading frequency between 4 and 20 Hz, and the ultrasonic testing frequency was 20 kHz. The stress ratio for both tests is $R = -1$. For ultrasonic testing, the effective cooling by distilled water with inhibitor was used to avoid temperature rise of the specimen. The fatigue results of Figure 14 shows that the fatigue strength by ultrasonic frequency is much higher than that by conventional frequency for the two grades of the tested steel. For J0 grade, the fatigue strength at 10^7 cycles is 220 MPa by conventional frequency and is 350 MPa by ultrasonic frequency. For J2 grade, the value is 270 MPa by conventional frequency and is 350 MPa by ultrasonic frequency. Klusak et al.[28] considered that the

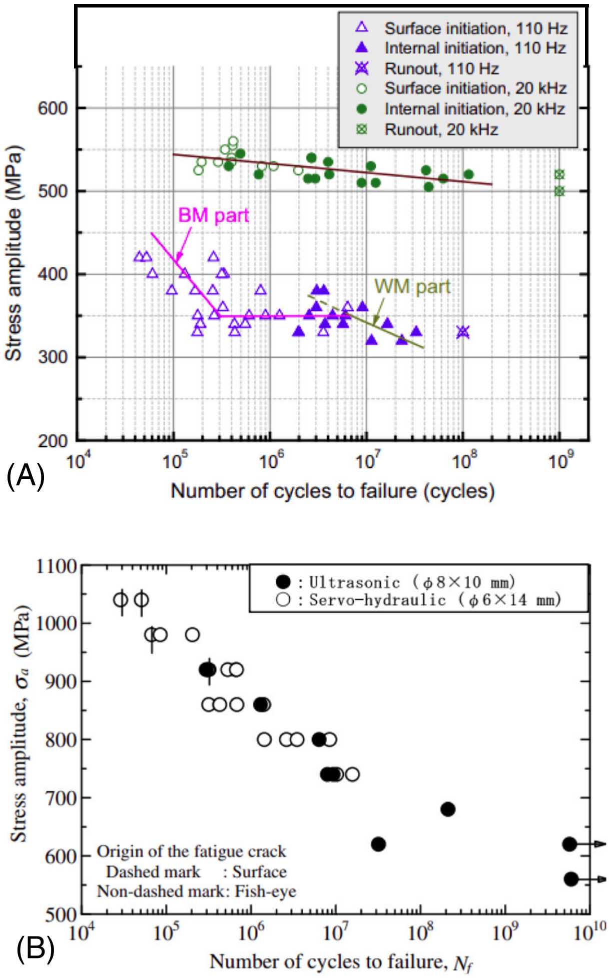

FIGURE 13 (A) S–N data of 25Cr2Ni2MoV welded joints at 20 kHz and 110 Hz showing remarkable frequency effect,[24] and (B) S–N data of SCM440 steel specimens with high tensile strength and almost the same control volume at 20 kHz and 20 Hz showing no frequency effect.[25] [Colour figure can be viewed at wileyonlinelibrary.com]

remarkable frequency effect for the steels with low strength, which is similar to the previously described two cases.[17,19] The difference in fatigue strength by low and high frequencies was explained by the need of time for plastic deformation during cycling. At ultrasonic fatigue testing, the period of the loading cycle is too short to activate dislocation movement. Thus, the activation of dislocation movements at ultrasonic frequency requires more cycles compared with low-frequency cycling. Another reason for the difference in fatigue strength resulted from low- and high-frequency tests is the specimen size effect.[25]

Without loss of generality, we should note some exceptional cases such as the results by Liaw et al.[29] who reported that the increase of loading frequency from 20 to 1000 Hz results in a substantial lower fatigue life and fatigue limit for a bcc material of structural steel as

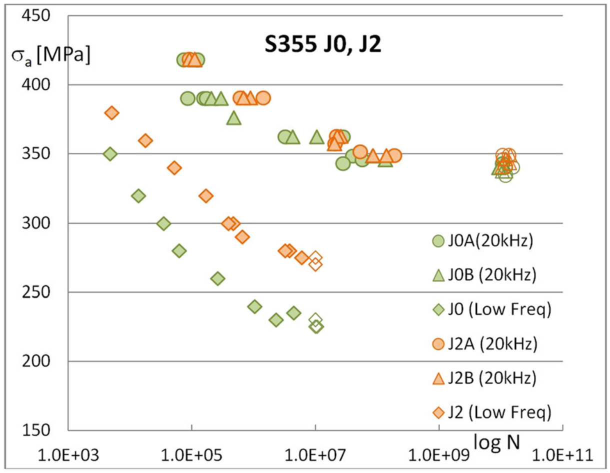

FIGURE 14 S–N data of two grades of S355 steel, showing ultrasonic frequency tests resulting in much higher fatigue strength than conventional frequency tests.[28] [Colour figure can be viewed at wileyonlinelibrary.com]

shown in Figure 15A. The test material was a reactor pressure vessel (RPV) steel (SA533B112) with the tensile strength of 716 MPa. The fatigue tests were conducted by electrohydraulic system of Model 1000 Hz 810 to produce 1000-Hz loading frequency and model 810 to produce 20-Hz loading frequency with both tests at the stress ratio of $R = 0.2$.

Liaw et al.[29] also performed the temperature measurement on tested specimens during fatigue testing and obtained that for the testing at 1000 Hz as shown in Figure 15B, the temperature of the specimen subjected to applied maximum stress 600 MPa increased to a steady state of about 95°C and jumped to 160°C at final failure, and the temperature of the specimen subjected to applied maximum stress 620 MPa reached about 175°C and then jumped to 235°C at final failure. For the testing at 20 Hz as shown in Figure 15C, the temperature of the specimen subjected to applied maximum stress 680 MPa just slightly increased from 22°C to 24°C and then jumped to 39°C at final failure. It is evident that the temperature rise and the highest temperature at 1000 Hz are much greater than those at 20 Hz, such that resulted in the shorter fatigue life and lower fatigue limit for the specimens tested at 1000 Hz.

As a summary for bcc type materials in this subsection and in the previously described two cases, the loading frequency effect on fatigue performance in HCF and VHCF regimes is generally pronounced with the higher frequency resulting in larger value of fatigue strength or fatigue life especially if the concerned bcc material is in a relatively low-strength state. When the strength of the bcc material is relatively high, the loading frequency effect on fatigue performance is possibly

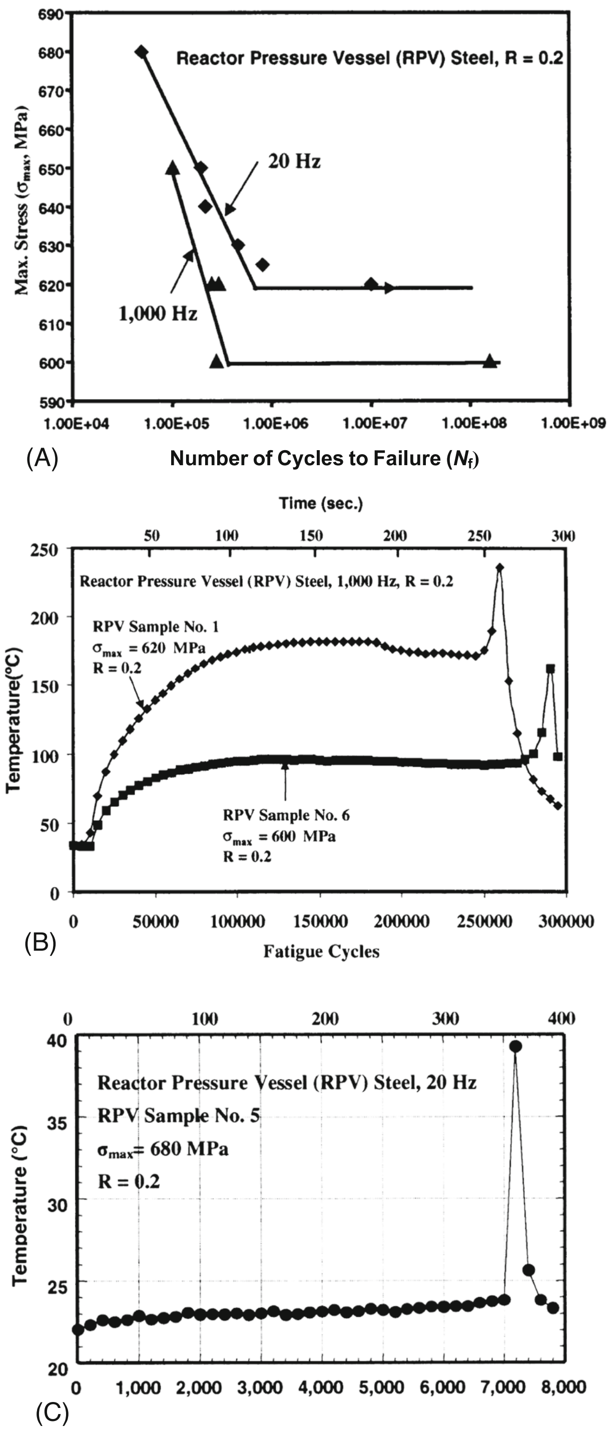

FIGURE 15 (A) S–N data of a reactor pressure vessel (RPV) steel tested at 20 and 1000 Hz, (B) temperature measurements of the specimens tested at 1000 Hz, and (C) temperature measurements of the specimen tested at 20 Hz.[29]

reduced or even vanished. The temperature rise during fatigue cycling at high frequencies especially at ultrasonic frequency is vital to influence the loading frequency effect, which may reduce the strength of the material and therefore degrade the related fatigue performance under high frequencies. In addition, the control volume of the tested specimens should be also paid attention to, which may cause a misleading result to interfere the evaluation of the loading frequency effect on related fatigue behavior. The above summary will be further addressed in Section 5.

4.3 | Propensities of hcp materials

Naturally, the type of hcp materials contains limited number of slip systems and the resulted mechanical behavior is basically sensitive to the applied strain rate and therefore to the temperature. Thus, it is anticipated that the loading frequency effect on the fatigue behavior of hcp materials will be possibly similar to the situations in bcc type materials. Here, we will see how they will behave in the following descriptions.

Titanium alloy is one of the typical hcp materials, which basically contains dominant hcp α phase and subsidiary bcc β phase. The fatigue behavior especially in HCF and VHCF regimes of titanium alloys has been extensively investigated because of their widespread engineering applications under cyclic loadings,[30–32] and thus, the loading frequency effect on the fatigue performance of titanium alloys has been paid great attention to as extensively described in the available review articles.[10–16]

Figure 16 is a typical example showing the effects of loading frequency on the fatigue strength of a titanium alloy in HCF and VHCF regimes.[33] The tested material was a Ti-6Al-4V with three heats (A, B, and C), and the values of tensile strength were 960 MPa for Heat A, 967 MPa for Heat B, and 906 MPa for Heat C, respectively. The microstructure of Heats A and C was nearly equiaxed α domains with the average grain size of about 7 μm, and that of Heat B was elongated α domains with the average grain size of about 20 μm. Fatigue tests of axial cycling were conducted by electromagnetic resonance at 120 Hz, high-speed servohydraulic at 600 Hz and ultrasonic at 20 kHz. All fatigue tests were in air and at the stress ratio of $R = -1$. For ultrasonic testing at 20 kHz, cold air was used to cool the specimen surface to let the surface temperature no higher than 50°C. Figure 16 shows the fatigue test results of the three heats at three loading frequencies.[33] It is interesting that the effect of loading frequency for Heats A and B (Figures 16A,B) is negligible and that for Heat C (Figure 16C) is significant. Takeuchi et al.[33] considered that the effect of loading frequency on fatigue behavior is in relation to the crack initiation type and the strength of material. Fatigue failure beyond 2×10^6 failure cycles of Heats A and B was induced by internal crack initiation. For such type of crack initiation, the effect of loading

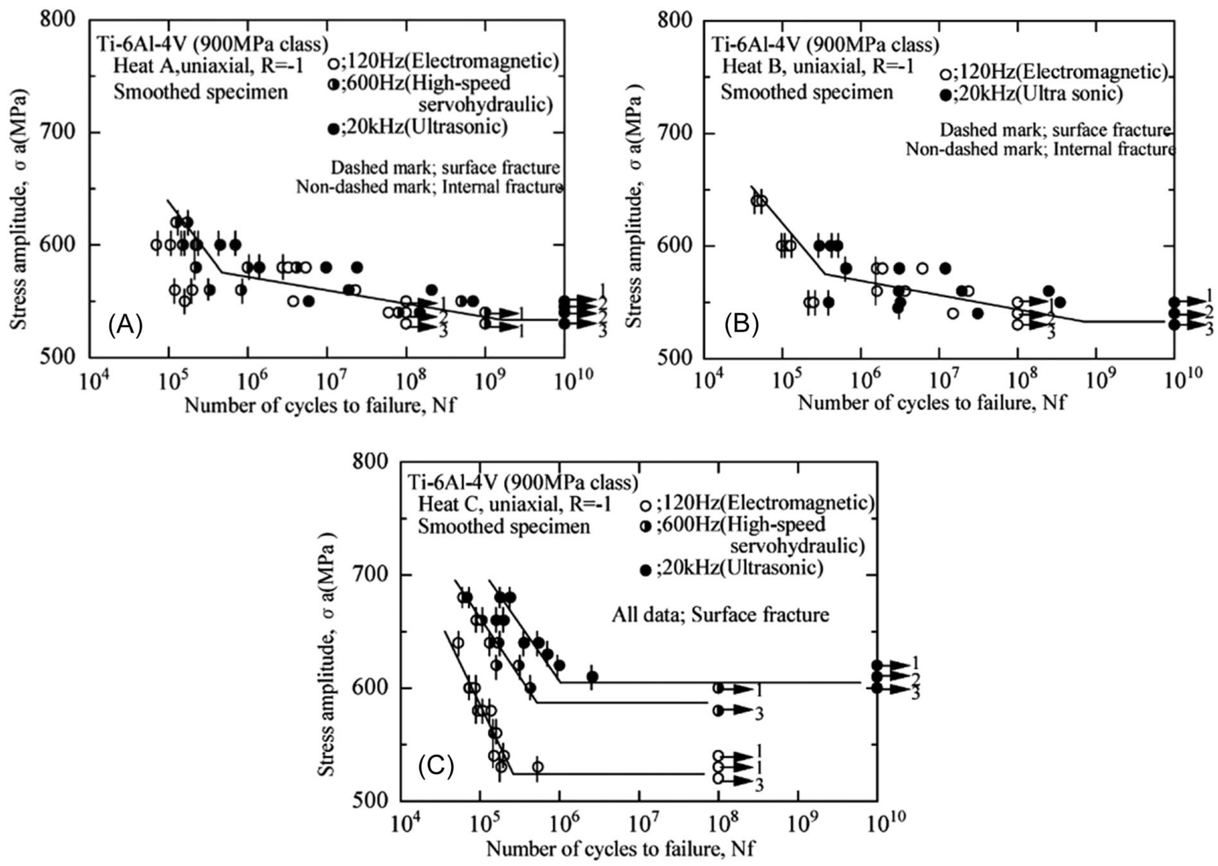

FIGURE 16 S–N data of tested Ti-6Al-4V at loading frequencies of 120 Hz, 600 Hz, and 20 kHz, (A) Heat A, (B) Heat B, and (C) Heat C.[33]

frequency on fatigue performance is insignificant, which is similar to the cases in high-strength steels. However, for the case of fatigue failure caused by surface crack initiation as happened in Heat C, the effect of loading frequency on fatigue strength is noticeable with higher frequency resulting in larger fatigue strength. Takeuchi et al.[33] explained that dislocation velocities are far slower than sonic speed and the initiation as well as the propagation of fatigue cracks is closely related to the localized surface plastic deformation, which cannot catch up the high-frequency loading and therefore results in the higher fatigue strength. The lower value of tensile strength of Heat C is also a possible reason to let the material with surface crack initiation and thus to have an evident loading frequency effect on fatigue performance.

Figure 17A[34] and Figure 17B[15] are two other examples of titanium alloys showing the S–N data obtained by conventional and ultrasonic frequencies. Figure 17A[34] is the results of a Ti-6Al-4V with the tensile strength of 968 MPa, and the fatigue testing was by ultrasonic cycling at 20 kHz with the stress ratio of $R = -1$. Morrissey and Nicholas[34] also performed temperature detection in the testing to show the maximum value of 85°C for the specimens without air cooling. Under air cooling situations, the peak temperature for the loading case of the maximum stress 350 MPa was 38°C and that for the loading case of the maximum stress 400 MPa was 47°C. Morrissey and Nicholas[34] claimed that such temperature change was impossible to affect the fatigue properties of the tested material. The fatigue testing results by ultrasonic frequency were compared with those by servohydraulic testing at 60 Hz as shown in Figure 17A, indicating that two sets of data were consistent with each other, that is, not frequency effect on fatigue strength existed for the tested titanium alloy. It is interesting that the fatigue specimens of this case were failed due to surface crack initiation, which is in contradiction to what stated by Takeuchi et al.[33] who argued that for the titanium alloys with surface crack initiation in fatigue failure, the higher loading frequency may induce larger value of fatigue strength.

Figure 17B is a recent case[15] showing the S–N data of a titanium alloy under two loading frequencies of 20 kHz and 55 Hz with the stress ratio of $R = 0.1$. It is seen that the fatigue lifetimes of the tested Ti-6Al-4V at the stress amplitudes of 350 and 375 MPa via both frequencies are

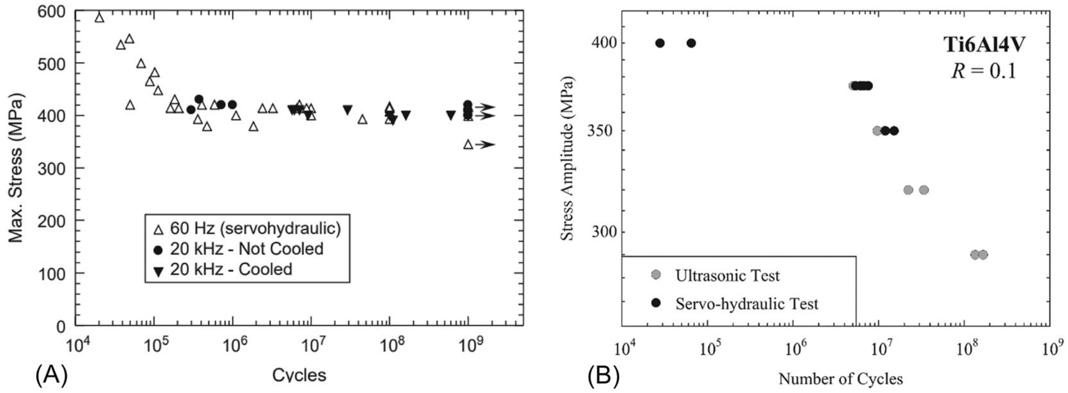

FIGURE 17 Two cases of S–N data for Ti-6Al-4V, (A) by loading frequencies of 60 Hz and 20 kHz,[34] and (B) by loading frequencies of 55 Hz and 20 kHz.[15]

almost identical, with the fatigue strength at 10^7 cycles being 359.7 MPa under servohydraulic frequency of 55 Hz and 356.3 MPa under ultrasonic frequency of 20 kHz. Thus, Fitzka et al.[15] claimed that the difference in fatigue life measured by ultrasonic frequency and conventional frequency is much smaller than the scatter of the values. It is interesting to note that in this case, the fatigue failure was caused by internal crack initiation for both frequency tests, which is consistent with what stated by Takeuchi et al.[33] who believed that for the cases of fatigue failure induced by internal crack initiation for titanium alloys, the frequency effect on fatigue strength is diminishing.

Figure 18A[22] is an example of commercially pure (c.p.) titanium showing the fatigue performance by ultrasonic cycling at 20 kHz and RB at 100 Hz. The c.p. titanium was of annealing state with the tensile strength of 522 MPa. It is seen from Figure 18A that the fatigue strength at 2×10^8 failure cycles for the testing at 100 Hz is 300 MPa and that for the testing at 20 kHz is 345 MPa, which means a moderate frequency effect exists with higher loading frequency resulting in larger value of fatigue strength.

Figure 18B[22] is the S–N data by ultrasonic cycling at 20 kHz and RB at 100 Hz for another type of titanium alloy Ti-6Al-7Nb with the tensile strength of 953 MPa. It is seen that the values of fatigue strength by both loading frequencies are within the same scatter band with the fatigue strength at 2×10^8 failure cycles for the testing at 100 Hz being 550 MPa and that for the testing at 20 kHz being 540 MPa, meaning that no notable frequency effect on the fatigue performance of this hcp material.

Here, another case of titanium alloys made by additive manufacturing (AM) was introduced.[35] It should be mentioned that in recent decade, AM technology has been increasingly applied to make metal parts for typical applications, especially in biomedical, automobile, and aerospace engineering sectors, and the fatigue performance of AMed metallic materials is one of the major concerns and has been paid great attention to in fatigue and fracture research field.[36–40] Thus, the effect of loading frequency on the fatigue behavior of AMed materials is a new topic although the available results are still limited in the literature. Figure 19[35] is a nice example showing the S–N data of a Ti-6Al-4V made by laser AM with the input energy density of 45.33 J/mm^3. Figure 19A is the case of the specimens subjected to stress relief treatment at 650°C for 3 h resulting in the tensile strength of 1089 MPa, and Figure 19B is the case of the specimens subjected to hot-isostatic-pressing (HIP) processing at 920°C and 1000 bar pressure for 2 h resulting in the tensile strength of 1022 MPa. The fatigue tests were conducted by a resonance testing machine at 59 Hz and by an ultrasonic testing system at 20 kHz. Pulse-pause mode of 200-ms cycling and 200-ms resting plus air cooling was adopted in the ultrasonic testing. It is seen that the variation of fatigue strength with failure cycles for the two cases under both frequencies of 59 Hz and 20 kHz is within a scatter band, suggesting that no notable frequency effect on fatigue performance for the AMed Ti-6Al-4V with two post-treatment conditions. Note also that the fatigue failure of stress relief treated specimens was due to internal crack initiation from the AM-induced defects and that of HIP-treated specimens was surface crack initiation in HCF regime and internal mode in VHCF regime.

By summarizing the cases of the hcp type materials in this subsection including the one made by AM, it is perceived that the effect of loading frequency on the fatigue behavior of hcp type materials typically titanium alloys is generally less pronounced with the data of fatigue strength or fatigue life obtained by high loading frequencies even ultrasonic vibration and by conventional loading frequencies being almost within a scatter band,

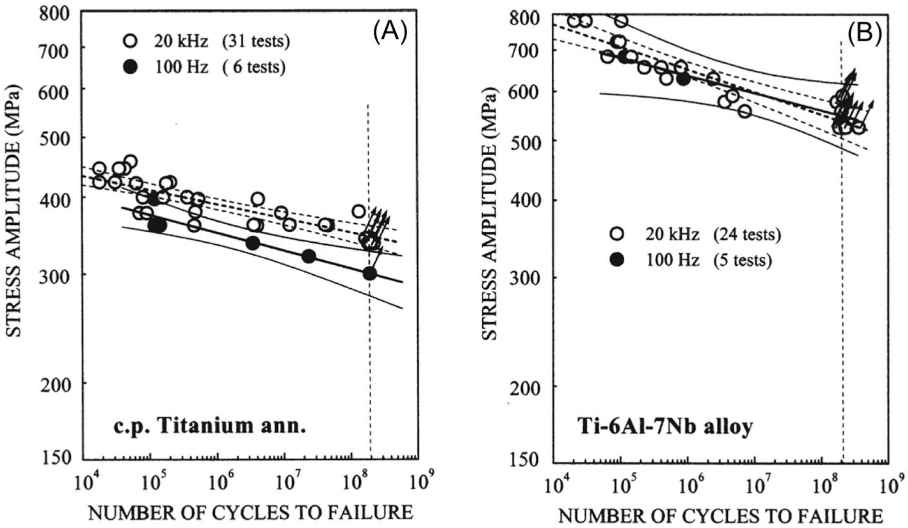

FIGURE 18 S–N data by ultrasonic cycling at 20 kHz and rotary bending at 100 Hz for (A) commercially pure (c.p.) titanium with annealing (ann.) state and (B) Ti-6Al-7Nb alloy.[22]

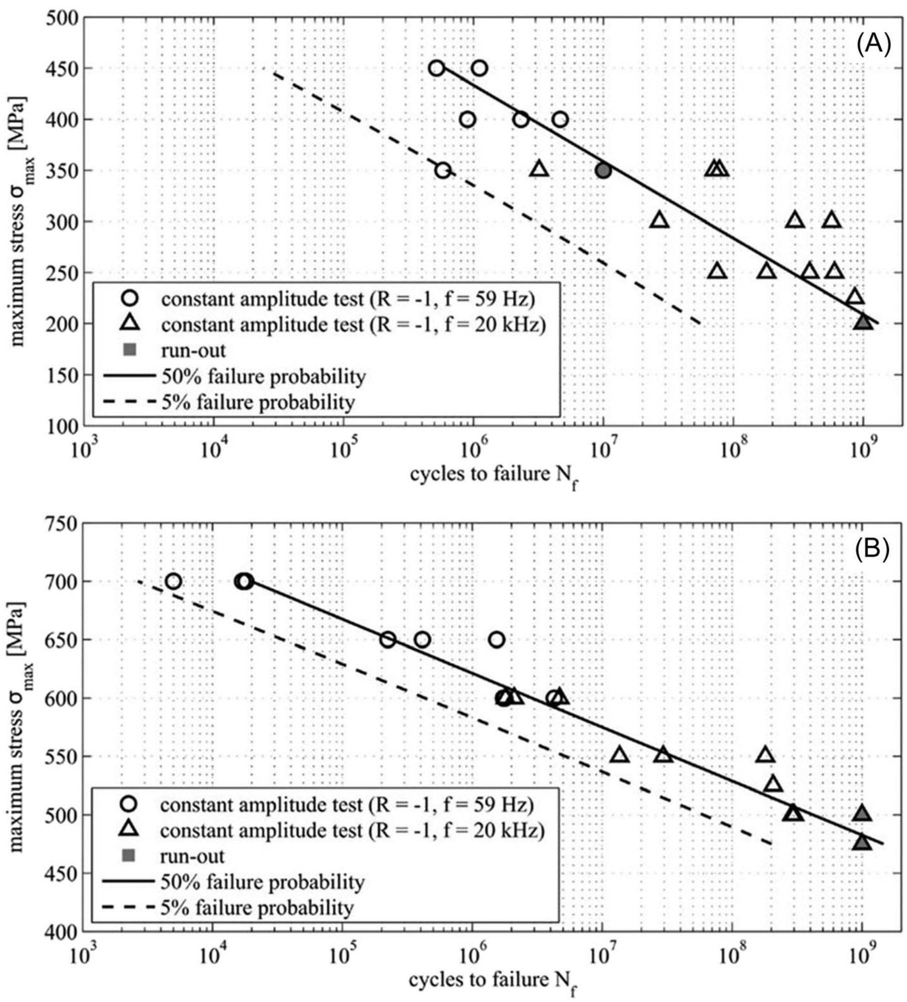

FIGURE 19 S–N data for a laser additively made Ti-6Al-4V under loading frequencies of 59 Hz and 20 kHz, (A) specimens subjected to stress relief treatment at 650°C for 3 h, and (B) specimens subjected to hot-isostatic-pressing treatment at 920°C and 1000 bar pressure for 2 h.[35]

especially for the hcp materials possessing high tensile strength and subjected to relatively low cyclic stress, that is, in VHCF regime with internal crack initiation. Nevertheless, it is also seen some divergent cases with notable loading frequency effect on the fatigue properties of relevant hcp materials, with higher loading frequency resulting in higher fatigue strength or fatigue life, which tended to happen in the hcp materials with relatively low tensile strength and subjected to relatively high cyclic stress with surface crack initiation. The above summaries will be further addressed in Section 5.

4.4 | Propensities of fcc materials

The character of fcc materials is with more slip directions in a slip plane, which makes them easy to slip and have good capacity of plastic deformation. Therefore, fcc materials are generally less sensitive to applied strain rate and environmental temperature. As a result, it is reasonable to anticipate that the loading frequency effect on the fatigue behavior of fcc materials is insignificant.

Figure 20 by Roth et al.[41] is an early example for an fcc material of electrolytic tough pitch (ETP) Cu with the tensile strength of 199 MPa, showing the result of loading frequency effect on fatigue performance. The test was under the frequency of 60 Hz and 20 kHz, and the method of oil cooling was used at the ultrasonic (20 kHz) cycling. It is seen from Figure 20 that for the fcc material of ETP Cu, there was no observable shift in fatigue strength by different loading frequencies in high-cycle and very-high-cycle regimes when adequate cooling was provided. Roth et al.[41] conducted the slip type analysis to reveal the prevalence of persistent slip at high stress conditions and etch pit slip at low stress conditions. Their observations illustrated that the specimens tested at 60 Hz and at 20 kHz had an essentially identical dislocation substructure, which was inconsistent with the phenomenon of negligible frequency effect on the fatigue performance of the tested material.

Figure 21 by Carstensen et al.[42] is another example of fcc material of austenitic stainless steel AISI 904L showing the value of fatigue strength as a function of failure cycles. RB at 160 and 200 Hz, and ultrasonic axial cycling at 20 kHz were used for the fatigue tests to investigate the loading frequency effect on fatigue performance. The ultrasonic test at 20 kHz was in a pulse-pause manner, with a pulse of 50 ms and a pause between 100 and 500 ms, and cooling fan was also used to avoid specimen temperature rise. Carstensen et al.[42] concluded no notable frequency influence on the fatigue lifetimes of the tested material as shown in Figure 21.

Figure 22[43] shows the S–N data at stress ratios of $R = 0.1$ and $R = 0.5$ in HCF and VHCF regimes for an age-hardened aluminum alloy 2024-T351 (fcc material) with the tensile strength of 473 MPa, which were performed via servo-hydraulic and ultrasonic testing. The loading frequency of servo-hydraulic testing was between 7 and 70 Hz for the case of $R = 0.1$ and was 70 Hz for case of $R = 0.5$. The loading frequency of ultrasonic testing was 20 kHz for both cases of $R = 0.1$ and $R = 0.5$, and a pulse-pause sequence plus forced-air cooling was adopted to avoid excessive specimen heating. The results of Figure 22 together with the analyses of data distribution indicate that the differences between mean fatigue lives from servo-hydraulic and ultrasonic tests lie within the data scatter, suggesting that the loading frequency effect on the fatigue strength of the tested 2021-T351 aluminum alloy is non-evident.

It is worthwhile to mention that in the time of 1990s and 2000s, a number of fatigue data at different loading frequencies up to VHCF regime were presented by Bathias,[44–46] including the data of nickel based alloy[45] and aluminum alloy,[46] showing the insignificant difference of fatigue performance under conventional and ultrasonic frequencies for fcc materials.

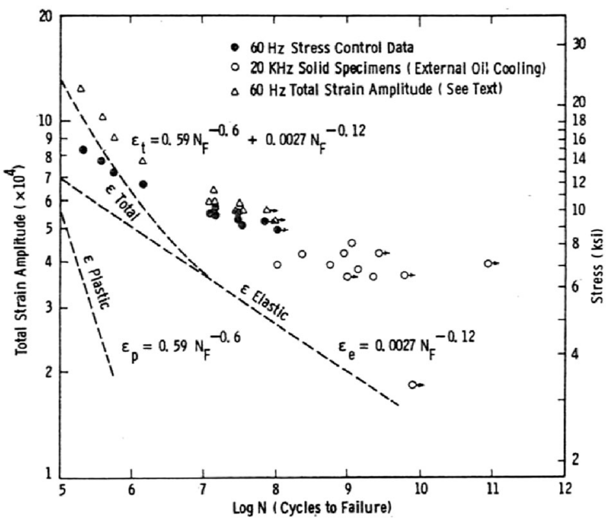

FIGURE 20 Fatigue data by the tests at 60 Hz and 20 kHz for an ETP (electrolytic tough pitch) Cu.[41]

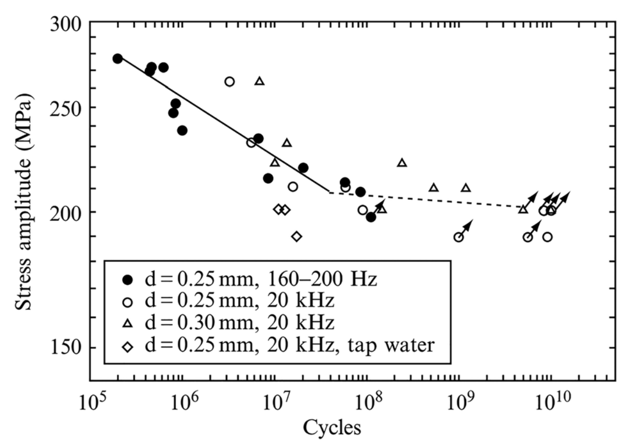

FIGURE 21 S–N data of AISI 904L austenitic stainless steel (fcc material) showing no notable frequency effect at 160–200 Hz and 20 kHz.[42]

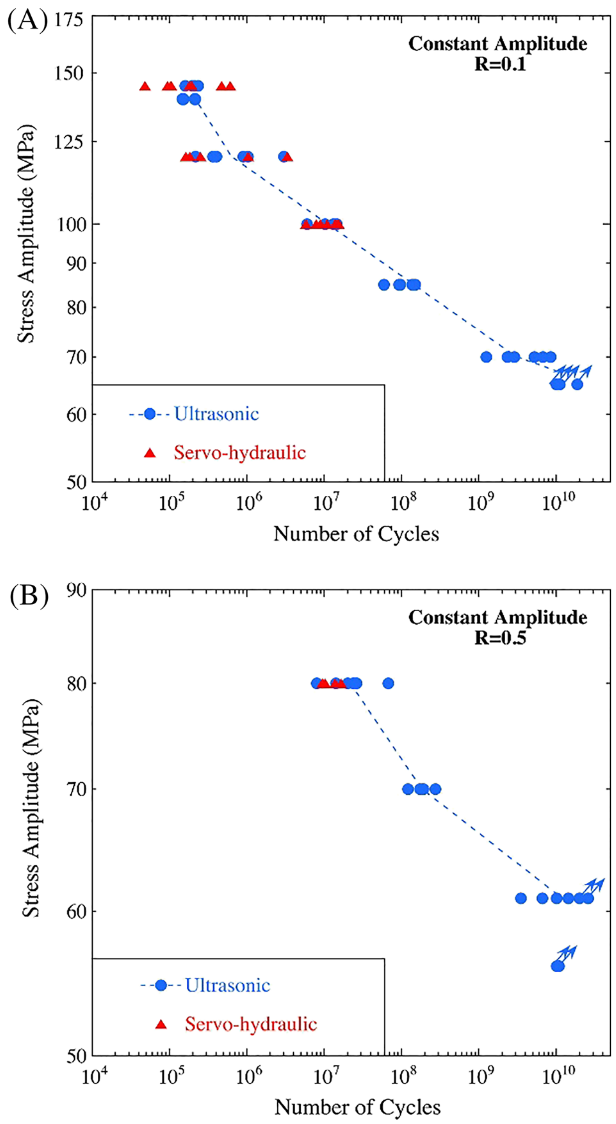

FIGURE 22 S–N data tested by ultrasonic and servo-hydraulic methods for an aluminum alloy 2024-T351, (A) stress ratio $R = 0.1$, and (B) stress ratio $R = 0.5$.[43] [Colour figure can be viewed at wileyonlinelibrary.com]

The cases illustrated in this subsection presented that the loading frequency effect on the fatigue performance of fcc materials is basically insignificant, that is, the fatigue properties in terms of fatigue strength or fatigue life obtained by the testing at high loading frequency even by ultrasonic vibration are approximately the same with the values by the testing at conventional frequency. This will be further addressed in Section 5.

5 | DISCUSSION

From the previous descriptions in Sections 2–4, we can acknowledge that the loading frequency effect (*LFE*) on the fatigue behavior of metallic materials is an issue in relation to several vital factors such as strain rate ($d\varepsilon/dt$), microstructure lattice type (M), temperature rise (T), and the strength (σ) of concerned materials. In other words, *LFE* is basically a function of $d\varepsilon/dt$, M, T, and σ:

$$LFE = f(d\varepsilon/dt,\ M,\ T,\ \sigma) \tag{6}$$

In the following, we will discuss the role of each factor in the influence on *LFE*.

5.1 | The role of strain rate

In order to quantitatively describe the role of strain rate in the influence of loading frequency effect on the fatigue performance of metallic materials, we draw a line plot of Figure 23 to illustrate the strain rate values corresponding to monotonic tests, conventional fatigue tests and ultrasonic fatigue tests. Generally, the strain rate of monotonic test for common mechanical properties is between 10^{-4} and 10^{-3} s^{-1}, that of conventional fatigue tests is between 10^{-1} and 10^{0} s^{-1}, and that of ultrasonic fatigue tests is at the level of 10^{2} s^{-1}. It is clear that the strain rate under ultrasonic frequency is about two or three orders of magnitude higher than that under conventional frequency. This large difference in strain rate due to different loading frequencies between ultrasonic and conventional fatigue tests will definitely cause the change of fatigue mechanism and related fatigue performance.[19,47–50] It is definite that the alteration of strain rate in relation to different loading frequencies is the most essential factor to cause the loading frequency effect on the mechanical behavior including the fatigue performance of the related materials. Therefore, it is certain that applied loading frequency does affect the fatigue behavior of the test material. Note that the sensitivity to strain rate effect is distinctly different for the materials with different microstructure lattice types. Thus, due to the difference in the microstructure characteristics of concerned materials and other factors, the phenomenon of *LFE* for some cases is remarkable, and for some other cases, *LFE* is possible to be suppressed. This will be further discussed in the following of this section.

Here, it should also be emphasized that the loading frequency effect is basically strain rate effect because the different states of loading frequency are equivalent to the different values of loading speed (with reversals). Loading frequency effect or strain rate effect will behave differently in different types of environment, and the strain rate effect may couple with the environmental effect. However, loading frequency effect and environmental effect are two independent aspects. The aim of this paper

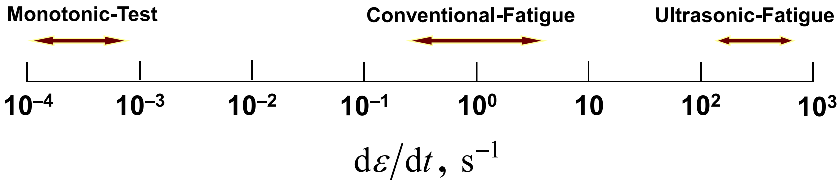

FIGURE 23 Values of strain rate in relation to monotonic-test, conventional-fatigue test and ultrasonic test. [Colour figure can be viewed at wileyonlinelibrary.com]

is focused on the loading frequency effect, and the investigations and explanations of environmental effect can be found in the literature.[13,51–54]

5.2 | The role of microstructure lattice type

To understand the loading frequency effect on the fatigue behavior of different types of metallic materials, we should mention that the process of fatigue crack initiation or fatigue damage is inevitably in relation to the localized plastic deformation of metallic materials. This is associated with the mechanism of dislocation movement and plastic deformation for relevant metallic materials.[55–58]

In general, the materials of bcc metals or the alloys with the microstructure dominated by bcc phase domains are sensitive to strain rate and therefore sensitive to loading frequency, which is due to the relatively large value of dislocation movement activation energy and higher related critical shear stress for dislocation movement of bcc crystals. This can be explained in terms of the Peierls–Nabarro stress (τ_{PN}) that is the critical stress required to move the dislocation through the lattice, which is[21]

$$\tau_{PN} = \frac{2G}{1-\nu}\exp\left[\frac{-2\pi a}{(1-\nu)b}\right], \tag{7}$$

where a is atomic plane spacing, b is atomic distance, G is shear modulus, and ν is Poisson's ratio.

Since Peierls–Nabarro stress is a short-range stress with regard to the dislocation core, therefore it is sensitive to the thermal energy in the lattice and hence to the test temperature.[21] At low temperatures, where thermal activity of dislocation motion is limited, the Peierls–Nabarro stress will be large. The relation between Peierls–Nabarro stress and strain rate is similar to what happens in the situation of temperature, that is, at high strain rate, the Peierls–Nabarro stress will be large for the lattice type with relatively low deformation capacity.

As known, the feature of slip systems for bcc crystals is of relatively small atomic plane spacing and large atomic distance. As a result, the Peierls–Nabarro stress for the metallic materials with bcc lattice is relatively high, and they are sensitive to strain rate and therefore to loading frequency, as shown in the cases[1,7,17,19,22–25,28,29] described in Sections 2, 3, 4.1, and 4.2. The loading frequency effect on the fatigue performance in HCF and VHCF regimes is generally pronounced with the higher frequency resulting in larger value of fatigue strength or fatigue life especially if the tested bcc material is in a relatively low-strength state. When the tensile strength of the bcc material is relatively high, the loading frequency effect on fatigue performance is possibly reduced or even vanished. This can be explained that the lower strength state possesses higher ability of dislocation movement and plastic deformation than the higher strength state as described in Section 2.[17] In addition, the temperature rise during fatigue cycling at high frequencies especially at ultrasonic frequency is vital to induce the loading frequency effect, which may reduce the strength of the material and therefore degrade the related fatigue performance under high frequencies. Thus, the loading frequency effect is jointly influenced by the strength of material and the temperature rise, which will be further discussed in Section 5.3.

In accordance to the concept above, the metallic materials with hcp lattice structure are very likely sensitive to strain rate and therefore to loading frequency. However, the realities were not so as illustrated in the cases[15,22,33–35] described in Section 4.3. It is seen that for most hcp material cases as presented in Figures 16A,B, 17A,B, 18B, and 19A,B, the loading frequency effect is negligible with the fatigue strength or fatigue life almost identical by conventional and ultrasonic frequencies. Note that for such cases, the tensile strength of the hcp materials is in a high level, and the crack initiation is almost from internal defects or other inhomogeneities. While for a couple of cases as presented in Figures 16C and 18A, the loading frequency effect does exist, with higher loading frequency resulting in larger fatigue strength, for which the tensile strength of the tested hcp materials is relatively low, the fatigue failure is not in very-high-cycle regime, and the crack initiation is at specimen surface. Thus, we may argue that for hcp materials, if the tensile strength is at a high level and subjected to a relatively low cyclic stress, the localized plastic deformation during crack initiation and early propagation is less affected by loading frequency or strain rate, meaning that the dislocation movement mechanism is almost the same at different loading frequencies. However, on the contrary, if the hcp materials are of relatively low tensile strength and subjected to relatively high cycling stress, the dislocation movement mechanism may differ at different loading frequencies, and the phenomenon of loading frequency effect may be evident, with the higher loading frequency resulting in larger fatigue strength.

Based on the above rule of dislocation movement under different loading frequencies, the materials with fcc microstructure lattice type will be less sensitive to strain rate or loading frequency. The cases[41–43] of fcc materials in reality do conform to this judgment as shown in Figures 20–22, in which the loading frequency effect is insignificant or vanishing with the fatigue strength or fatigue life almost the same by conventional and ultrasonic frequencies. This is ascribed to the high capacity of dislocation movement of fcc materials and the localized plastic deformation during crack initiation and early growth is less affected by strain rate or loading frequency.

In fact, the phenomenon of cyclic softening/hardening during fatigue process is also in relation to the lattice type of metallic materials. In general, the softening/hardening tendency of bcc and hcp type materials is more evident than that of fcc type materials, which is also due to the relatively high Peierls–Nabarro stress for the bcc and hcp materials. It should be noted that the phenomenon of cyclic softening/hardening during fatigue process is sensitive to the strength state of the materials. For low-strength state, the softening/hardening effect will be quite evident, whereas for high-strength state, such effect will be diminishing, although in some cases, cyclic softening may occur. This is attributed to the deformation capacity born by the low-strength state materials.[21]

5.3 | The role of specimen temperature rise during cycling process

During fatigue testing by ultrasonic frequency, for example, 20 kHz, the strain rate is as high as in the order of magnitude of 10^2 s^{-1} as depicted in Figure 23. Because of the very high strain rate, it is possible that the energy dissipation with regard to the elastic and plastic deformation will cause the temperature rise of the tested specimen. Again, bcc and hcp type materials are generally sensitive to this effect, whereas fcc type materials are less sensitive to it, due to the relatively low critical stress required for dislocation movement. For this, cooling procedures on tested specimen surface may accelerate the heat transfer and suppress the temperature rise. The method of pulse-pause loading (or called intermittent loading) control in ultrasonic cycling will reduce the cycling intensity and thus ease the extent of energy dissipation. It is sure that temperature rise will lower the strength of the material and induce loading frequency effect. The temperature rise induced by ultrasonic frequency will reduce the strength of the material, and will change the related strain rate response, which will degrade the fatigue performance. Therefore, it is very important to take the measure of air cooling or pulse-pause control or both to reduce the temperature rise of the tested specimen in ultrasonic frequency testing. Otherwise, the possible temperature rise of the specimen will reduce the strength of the material and thus promote the unexpected frequency effect.

It should be reiterated that the cooling measures of pulse-pause (intermittent) loading and/or compressive air blowing should be taken in the fatigue tests at ultrasonic frequency to avoid temperature rise of the specimen. Otherwise, the fatigue test data will be invalid because the strength state of the material will be changed due to the temperature rise. There is an interesting phenomenon that the process of pulse-pause (intermittent) loading mode may result in higher fatigue life,[59] which still needs more investigations.

5.4 | The role of material strength state of concerned material

The yield strength or tensile strength under monotonic loading of a material is its ability to resist the subjected loading from plastic deformation, and the value of the strength is essentially determined by the chemical composition and the microstructure characteristics of a given material.

For the metallic materials at low-strength state, the loading frequency effect on fatigue performance is evident, in which ultrasonic frequency leads to higher fatigue strength. For the metallic materials at high-strength state, the loading frequency effect is diminishing, in which the difference in fatigue strength under conventional and ultrasonic frequency is marginal. This tendency of material strength state versus loading frequency effect prevails especially in bcc and hcp type metallic materials, which was described in Sections 2, 3, 4.1, 4.2, and 4.3. Note that the phenomenon of cyclic softening and hardening will alter the original strength state of the material and will be a coupled factor influencing the trend of loading frequency effect.[12,60–64] This may change the original strength state of the material and thus the related loading frequency effect may be altered.

The role of material strength state of concerned material is also addressed in the previous discussion of "the role of microstructure lattice type" and it is not necessary to reiterate here.

5.5 | The role of control volume or size effect

In the investigations of loading frequency effect on the fatigue performance of metallic materials, different types of loading modes such as RB with conventional frequency and axial vibration with ultrasonic frequency were often used, which happened in the studies[17, 19, 22, 44] and described in Sections 2, 3, 4.2, and 4.4. In the past two decades, the effect of loading type on fatigue performance has been reported by the researchers in fatigue research community.[19,65–68] With this regard, Murakami et al.[27] first proposed the concept of control volume to interpret the effect of loading type, in which the control volume was defined as the volume that bears large than 90% of the maximum loading stress. Later on, Li et al.,[65] Shiozawa et al.,[66] and Nakajima et al.[67] accomplished VHCF tests under conventional axial loading (CAL) and RB, and demonstrated the results of fatigue strength under RB higher than that under CAL, which is mainly attributed to the value of control volume for the RB specimen smaller than that for the CAL specimen. Recently, Sun et al.[68] and Hu et al.[19] developed the method of probability-statistics analysis combined with control volume concept to reconcile the fatigue data under RB at 52.5 Hz, EA at 120 Hz, and UA at 20 kHz. It is clear that for the feature of stress gradient under RB, the control volume of the specimen is substantially smaller than that under CAL, and thus, the CAL specimen has a higher risky possibility than the RB specimen, which leads to lower fatigue strength by the CAL method than by the RB method. It should be mentioned that the effect of control volume is basically the issue of size effect in relation to the defects contained in the concerned specimens. In fact, the effect of control volume or size effect on the fatigue behavior of metallic materials is not the main topic of this review article, which will be addressed in detail in our future investigations.

6 | CONCLUDING REMARKS

In the beginning of this article, we mentioned a question that is frequently asked by the researchers in fatigue research community: Does loading frequency affect the fatigue performance and behavior of metallic materials? Based on the common sense of strain rate effect, the answer is yes. Basically, the effect of loading frequency is the strain rate effect induced by the cycling speed. Then, the subsequent question is how is such a loading frequency effect? In this article, we used our two previous cases and the results in the literature to comprehensively address this question. In the end, we would like to draw the following brief summaries.

1. For low-strength metallic materials, such as structural steels and low-strength state high-carbon steels, the effect of loading frequency is remarkable, with the testing by ultrasonic frequency resulting in higher fatigue strength than that by conventional frequency.
2. For high-strength metallic materials, such as high-strength state of high-carbon steels, the effect of loading frequency is diminishing, with the values of fatigue strength almost identical under both conventional and ultrasonic frequencies.
3. The metallic materials with bcc lattice are generally sensitive to loading frequency effect, with the higher loading frequency resulting in larger value of fatigue strength, especially for the cases that the bcc materials are with low-strength state. If the bcc materials are with high-strength state, the loading frequency effect will be suppressed.
4. Most cases of hcp materials are generally less sensitive to loading frequency effect, which are normally with high-strength state and subjected to relatively low cycling stress, although some exceptional cases possess notable loading frequency effect, with higher loading frequency resulting in higher fatigue strength or fatigue life, which tends to happen in the hcp materials with relatively low-strength state and is subjected to relatively high cyclic stress with surface crack initiation.
5. The metallic materials with fcc lattice are less sensitive to loading frequency effect. This is because fcc materials are less sensitive to strain rate effect due to the relatively low activation resistance to dislocation movements.
6. Special attention should be paid to the temperature rise of the tested specimen under high frequencies, especially under ultrasonic frequency. Temperature rise will cause the variation of material strength and the related strain rate may vary, which will result in the variation of fatigue strength.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Youshi Hong https://orcid.org/0000-0003-3425-6808

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