Flow Stress Measurement and Dynamic Response Analysis of Hot Compression Test Machine at High Strain Rates

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Flow stress is the most important information for hot strip rolling as it affects the rolling force and the thickness of the rolled product. A high-speed compression test up to a strain rate of 300 s⁻¹, which is the compression speed of 3 600 mm·s⁻¹ for a 12-mm-high cylindrical specimen, is necessary as a strain rate of 100–300 s⁻¹ is the normal rate in the production of hot-strip-rolled steel sheets. An experiment is conducted using a servo-hydraulic compression test machine, which enables a high compression speed and a high temperature, but the oscillation is observed in stress-strain curve at high strain rate over 50 s⁻¹. To determine the natural frequency of the compression test machine, the Savitzky-Golay filtering method is used for regression and the fast Fourier transformation (FFT) is adopted. To explain the mechanism of this phenomenon, a spring–mass–damper model is used and the results are compared with the FFT analysis result. After eliminating oscillation on the time versus load curve, a flow curve is obtained by inverse analysis, which compensates for the nonuniform strain rate, the inhomogeneous distribution of deformation, and the temperature increase during deformation.

KEY WORDS: high strain rate; hot compression test machine; flow stress; oscillation; inverse analysis.

1. Introduction

The use of automation, artificial intelligence, and data science technology to operate factories has recently been a crucial issue to increasing productivity in bulk metal forming. To realize this, the optimization of processing parameters such as strain, strain rate, and temperature, which are known to affect mechanical properties after processing, is necessary. Therefore, deformation tests to obtain the flow curve, which describes the plastic deformation behavior of a material, are being conducted. When carrying out experiments, actual test conditions are inhomogeneous. Moreover, to increase the production speed, consistent experiment data under high-speed conditions is necessary. This is why the tests should be performed under a wide range of conditions. Precise deformation data under a static condition can be easily obtained. However, forming parameters under dynamic conditions appear to adversely affect test results. For example, at elevated temperatures, there are problems such as an inhomogeneous temperature distribution caused by friction, and internal heat generation due to severe deformation. To obtain precise flow curve data, such effects should be taken into account. Yanagida and coworkers suggested a novel method of correcting them by inverse analysis.1,2) This method is not just a simple data regression method, because its FE calculation is based on a physical formulation. The optimum flow curve calculated by inverse analysis can be used to obtain material genome, which is a group of constitutive equations to describe the kinetics of microstructural evolution of a material.3)

The compression test at a high strain rate can cause unwanted effects that leads to inaccurate stress-strain data. A nonuniform strain rate due to the acceleration of the main ram is one of them. By inverse analysis, the problem can be partly solved as the flow curve is ideally calculated at a uniform strain rate. An experimental method of maintaining the strain rate throughout an experiment has also been developed.4) The oscillation appearing in stress-strain measurement results at a strain rate of over 50 s⁻¹ is another problem. At a strain rate of over 1 000 s⁻¹, a Split-Hopkinson pressure bar (SHPB) machine is used, which takes advantage of the stress wave propagation principle (a stress wave is generated by a shock between long bars).5) Some researchers have applied a pulse shaping method to correct the oscillation caused by the dispersion effect.6) However, an SHPB equipment is hardly used at strain rates lower than 500 s⁻¹. The reason is that the pressure bars composing the equipment must be so long that a large facility is required to accommodate the equipment.7) Accordingly, a servo-hydraulic test machine is preferred to an SHPB when the test strain rate is lower than 500 s⁻¹. Below a strain rate of 1 s⁻¹, which is defined as the quasi-static region, a servo-hydraulic test machine is mostly used and oscillation does not appear. However, it appears when the strain rate is over 50 s⁻¹. The main reported cause is stress
wave propagation due to shock between the components of
the test machine. In the strain rate range between 50 and 300
s\(^{-1}\) (defined as a high strain rate in hot forming research),
dynamic and quasi-static behaviors occur simultaneously.
Therefore, for the above-mentioned reasons, the material
deformation data in this range is the most difficult to obtain
precisely. In particular, the flow curve at a high strain rate
can be used for the hot rolling, forging, and extrusion of
steel because the normal deformation speed can reach the
strain rate range for these processes.

There have already been several attempts to address the
issue. Haugou et al.\(^8\) carried out experiments and numerical
simulations to analyze the elastic response of a compression
test machine, and proved that the mass and stiffness of the
system are major parameters affecting the response. Kopp
et al.\(^9\) adopted a selective smoothing method to correct
signals. Diot et al.\(^10\) proposed a two-step sequential identi-
fication model based on an inverse analysis to optimize the
structural parameters and obtain the dynamic behavior of a
material. They used a linear regression method to evaluate
the natural frequency of a compression test machine. Zhu
et al.\(^11\) used an autoregressive method to fit the data and
proposed spring-mass-damper model with a single degree
of freedom to explain the elastic phenomenon.

This paper mainly focuses on a new methodology of
obtaining a flow curve at a high strain rate that is indepen-
dent of the elastic response, and we propose a new numeri-
cal process to correct the oscillating behavior. In Section 2,
the experimental steps used to obtain a stress-strain curve
using a servo-hydraulic compression test machine are elabo-
rated. In Section 3, a dynamic response analysis based on
numerical fitting and fast Fourier transformation (FFT) is
presented; this method can be used to confirm the natural
frequency of a test machine. Finally, a theoretical investiga-
tion of the model used to analyze the machine is presented.
The stress oscillation equation derived using the spring-
mass-damper model is compared with the FFT result, and it
is found that the vibrational behavior obtained from the FFT
is in agreement with the equation. Section 4 addresses the
use of the high-pass filter technique to obtain filtered load
data, and a stress-strain result that is fully independent of the
elastic response of the test machine is displayed. The non-
uniformity of the strain rate is corrected by inverse analysis,
and the final flow curve, obtained using a constitutive law
that reflects metallurgical phenomenon, is presented.

The flow curve obtained from this study can be used in
the generalized description of flow curves\(^2\) and in material
genome research\(^12,13\) at high strain rates. Material genome
research on different types of material at strain rates of less
than 50 s\(^{-1}\) has already been discussed by several research-
ers. By using techniques in current research, and eventu-
ally obtaining more accurate stress-strain curves, the strain
rate range is expected to expand to over 50 s\(^{-1}\) in future
research.

2. Experimental Section

2.1. High Speed Compression Test Machine

A compression test machine is used for the test because
it has an advantage over a tensile test machine in that it
provides material data up to a large strain. A photograph
and a schematic illustration of the 15 ton Thermecmaster-
Z high speed hot forming simulator used in this study is
shown in Fig. 1.

The machine can simulate a hot forming production
environment at a small scale. The maximum strain rate
and temperature of the machine are 300 s\(^{-1}\) and 1 400°C,
respectively. The load capacity of the machine is 150 kN.
The ram position is measured using a linear voltage dif-
erential transformer (LVDT). The load is measured using
a strain-gauge-type load cell positioned beneath the lower
die. The machine adopts induction heating to raise and
hold the temperature. To achieve this, a spiral induction
coil is installed inside the adiabatic chamber to surround
the specimen. A PID feedback system sending the signal
from a thermocouple welded at the midpoint of the speci-
men height is used to control the test temperature in real
time to ensure that the temperature is uniformly maintained
throughout the test. Also, a water and gas type (N\(_2\)) cool-
ing system is equipped in this machine to rapidly quench
the heated specimen to freeze its grains. The measurement
system of the machine acquires load, stroke, and time data
during the compression. The top and bottom dies are made
of silicon nitride (SiN\(_4\)), known to have a very high stiff-

![Fig. 1. Photograph (left) and schematic illustration (right) of 15 ton Thermecmaster-Z hot compression test machine. (Online version in color.)](image-url)
ness, a low density and a high heat resistance, making it an ideal material for high-speed hot compression tests. Mica is inserted in both the upper and lower contact areas between the tool and the specimen to minimize the friction and heat transfer effect. To conduct a high-speed compression test at a uniform strain rate, the ram velocity should be carefully controlled. Hence, it is programmed to move in accordance with Eq. (1), derived from definitions of the true strain and true strain rate, assuming a uniform strain rate throughout the test. Here, $h_0$, $\dot{\varepsilon}$, $V$, and $t$ denote the initial height of the specimen, the strain rate, the ram velocity, and time, respectively.

$$V = \dot{h}_0 \exp(-\dot{\varepsilon}t) \quad \text{……………….. (1)}$$

Since it is very difficult to suddenly initiate compression at a high speed, a run-up method is applied to control the stroke movement. However, this run-up control is mainly responsible for the excitation of an elastic response, the principle of which will be explained in Section 3.

2.2. Experimental Conditions

The materials used in this study are 0.2% carbon alloyed steel (JIS-S20C), A5083BE-O aluminum alloy, and Inconel 718 nickel alloy, and their chemical compositions are shown in Table 1. Each specimen used in the experiment has a cylindrical shape with a height of 12 mm and a diameter of 8 mm, which is the specimen size recommended in ASTM E209-00.5)

Figure 2 shows the thermal processing history in the experiment. The temperature is increased from room temperature to the target temperature at a rate of $10^\circ$C·s$^{-1}$ and maintained at this temperature for 20 s to minimize the inhomogeneity of the heat distribution within the specimen until the specimen is compressed. The reduction rate in the experiment is set to 75% of the original height for all conditions. Finally, the specimen is cooled to room temperature using the N2 gas.

The axial compression test is conducted at temperatures of 800, 900, and 1000°C (two-thirds of melting point) for JIS-S20C, 380°C for A5083BE-O (two-thirds of melting point), and 882°C for Inconel 718 (two thirds of melting point). The strain rates chosen for the experiment are 1, 50, 100, 150, and 200 s$^{-1}$.

2.3. Experimental Results

From the compression test using the 15 ton Thermacmaster-Z simulator, axial stress-strain data is obtained, which is calculated in consideration of the bulging effect due to the friction between the die and the specimen. From the axial stress–strain curve of JIS-S20C in Fig. 3, oscillation does not occur in the test result at 1 s$^{-1}$, but it is observed when the strain rate is 50 s$^{-1}$ or higher.

Therefore, the measurement of the stress-strain curve becomes inaccurate. To separate the effect of oscillation from stress–strain curve, the analysis of the elastic effect of the compression test machine is necessary, as discussed in more detail in the next section.

3. Dynamic Response Analysis at High Strain Rate

3.1. Regression Method

The oscillatory response observed in the test result is assumed to have been caused by the elastic behavior of the test machine. The stress result can be defined as

$$\sigma_{exp} = f(\sigma_n, \sigma_{noise}) \quad \text{……………….. (2)}$$

Here, $\sigma_{exp}$ denotes the experimental stress result, $\sigma_n$ denotes the stress of the specimen, and $\sigma_{noise}$ denotes the stress caused by the noise effect. Among the several fre-
frequency responses reflected in the load data, the natural frequency of the test machine due to the compression mode should have the highest amplitude. Since the natural frequency is excited by the inherent features of the machine, the following three assumptions are necessary in the analysis of the dynamic response:

1) There exists a frequency at which its amplitude is much higher than any other frequencies.
2) The natural frequency should not be affected by experimental conditions such as strain rate and temperature.
3) The material of the specimen should not strongly affect the natural frequency.

The first procedure conducted in the analysis is the regression of the oscillating curve. Among the many smoothing methods, three types are employed, which are a 9th-order polynomial function, an exponential function, and the Savitzky-Golay filtering method.\(^{17,18}\) The Savitzky–Golay filter is a data smoothing filter that fits successive subsets of adjacent data points with a polynomial function of a certain order by the least-squares approximation. By using this method, the precision of the data can be improved, and the overall signal tendency is not distorted. The most ideal regression method should be that where the regression curve passes through the center of the oscillating parts of the original curve. When the reduction rate is high, 9th-order polynomial and exponential functions do not satisfy this requirement. On the other hand, Savitkky-Golay filtering, chosen as the main regression method in this study is clearly satisfactory. And by taking a subset of the data, it not only eliminates the vibration around the adjacent data to be fitted but also minimizes the effect of the fluctuation of the relatively distant noise data. This allows to obtain an excellent fitting curve by repeating moving subset data which is called the movement of window. The process is illustrated in Fig. 4.

The orders of the polynomial in this study are 7 (50 s\(^{-1}\)), 5 (100 s\(^{-1}\)), 3 (150, 200 s\(^{-1}\)), which are found to be the most appropriate numbers for satisfying condition 1 mentioned above after many trials. The number of data in the subsets is selected to be 999. Attention is required when determining these numbers since erroneous numbers can lead to overfitting or underfitting. The results of filtering are shown in Fig. 5.

After filtering, for the purpose to make the original experimental data \(F^{exp}(t)\) vibrate along the time axis, the filtered data \(F^{SG}(t)\) is subtracted from \(F^{exp}(t)\).

\[
\Delta F^{corr}(t) = F^{exp}(t) - F^{SG}(t) \quad \text{(3)}
\]

As a result, the residual data \(\Delta F^{corr}(t)\) is obtained, as shown in Fig. 6.

### 3.2. Fast Fourier Transformation

The above results clearly show the oscillation of the fitted data in the time domain. To observe the oscillation in the frequency domain to find the natural frequency of the compression test machine, which should always be the same regardless of the temperature, strain rate, and material, fast Fourier transformation (FFT) is selected and applied to
\[ F_{\text{corr}}(t) \] results at strain rates of 50, 100, 150, and 200 s\(^{-1}\) and temperature of (a) 800, (b) 900, and (c) 1000°C. (Online version in color.)

\[ F_{\text{corr}}(t) \] results at strain rates of 50, 100, 150, and 200 s\(^{-1}\) and temperature of (a) 800, (b) 900, and (c) 1000°C. (Online version in color.)

\[ F_{\text{corr}}(t) \] results at strain rates of 50, 100, 150, and 200 s\(^{-1}\) and temperature of (a) 800, (b) 900, and (c) 1000°C. (Online version in color.)

\[ F_{\text{corr}}(t) \] results at strain rates of 50, 100, 150, and 200 s\(^{-1}\) and temperature of (a) 800, (b) 900, and (c) 1000°C. (Online version in color.)

\( \Delta F_{\text{corr}}(t) \). The FFT result for JIS-S20C is shown in Fig. 7, and those for A5083BE-O and Inconel 718 are shown in Fig. 8. From Fig. 7, it is confirmed that a sharp peak appears when the frequency is 1000 Hz, which is concluded to be the natural frequency of the test machine because it is not affected by the experimental conditions or material. From Figs. 7 and 8, it can be seen that the amplitude at the natural frequency increases with the strain rate. In Fig. 7, the natural frequency does not change and remains the same at 1000 Hz, and it is concluded that it is not affected by the type of specimen. For the theoretical discussion of this phenomenon (the independence of the natural frequency and the dependence of the oscillation amplitude on the strain rate), a stress oscillation model is presented in the next section.

3.3. Stress Oscillation Model

To explain the elastic response of the test machine at a high strain rate, a Voigt model based on a spring-damper system is employed as shown in Fig. 9.

Here, a system with multi degrees of freedom system is reduced to an equivalent system with a single degree of freedom. \( k_{sys} \) denotes stiffness, \( c_{sys} \) is the damping coefficient, and \( m_{sys} \) is the mass of the integrated system which consists of many parts including the joints of these parts. These parts and the joint condition must affect the natural oscillation. In this paper, those were assumed as a series connection aligned in the oscillation axis direction. From the model, a second-order ordinary differential equation can be formulated as

\[ m_{sys} \ddot{U}_x + c_{sys} \dot{U}_x + k_{sys} U_x = 0. \quad ........................ (4) \]

Here, \( U_x \) stands for the longitudinal displacement of the particle of the system. As boundary conditions, \( U_x(0) = 0 \) and \( \dot{U}_x(0) = V_0 \) are employed. A nonzero \( V_0 \) is required.
because the velocity in the experiment must be sufficiently high to maintain a uniform high strain rate throughout the experiment. Accordingly, the ram is programmed to be accelerated in the run-up. Solving the above equation, we obtain the following formulation:\textsuperscript{11,19)

\[ U_x = \frac{V_0}{w_d} e^{-\zeta w_d t} \sin(w_d t). \text{......... (5)} \]

\( \zeta, \; w_{ns}, \text{ and } w_d \) are the critical damping coefficient, the natural frequency of the system, and the natural frequency including the damping factor, and are defined as

\[ \zeta = \frac{c_{sys}}{2m_{sys} k_{sys}}, \; w_{ns} = \sqrt{\frac{k_{sys}}{m_{sys}}}, \text{ and } w_d = w_n \sqrt{1 - \zeta^2}, \]

respectively. The strain and stress oscillations can be derived using Eq. (5) (longitudinal wave equation). The strain oscillation is expressed as

\[ \varepsilon_{sx} = \frac{dU_x}{dx} = \frac{V_0}{w_d} e^{-\zeta w_d t} \cos(w_d t + \phi) \frac{dt}{dx}. \text{......... (6)} \]

Here, \( \frac{dx}{dt} = v \) (\( v \) is a representative propagation velocity of the elastic wave and defined as \( v = \sqrt{\frac{E}{\rho}} \).)

Thus, Eq. (6) can be expressed as

\[ \varepsilon_{sx} = \frac{V_0}{w_d} e^{-\zeta w_d t} \cos(w_d t + \phi) \cdot \frac{\rho}{E}, \text{......... (7)} \]

where \( \phi \) is the phase change. By multiplying the strain oscillation and Young’s modulus \( E \), the following stress vibration equation can be obtained.

\[ \sigma_{noise} = \sigma_{sx} = E \varepsilon_{sx} = \frac{V_0}{w_d} \cdot \sqrt{\rho E} \cdot e^{-\zeta w_d t} \cdot \cos(w_d t + \phi). \text{......... (8)} \]

By analyzing this stress oscillation equation, several features are revealed to exist. First, from the stress oscillation model, it can be seen that the stress amplitude increases with the initial ram velocity \( V_0 \). Since a high \( V_0 \) is achieved owing to the initial acceleration in the run-up before compression starts, it can be concluded to be the main reason for the response. However, the control of the run-up process is also necessary to maintain the initial strain rate. Therefore, oscillation in stress–strain curve owing to run-up process should be eliminated through data filtering method.

Three conclusions can be drawn from this equation. 1) The natural frequency of the damped vibration \( \omega_d = \omega_n \sqrt{1 - \zeta^2}, \; w_d = w_n \sqrt{\frac{4m_{sys} k_{sys} - c_{sys}^2}{4m_{sys}^2}} \) is not affected by the...
strain rate and depends on the stiffness and mass of the system, which was also verified by Haugou et al. The natural frequency can be increased by increasing the stiffness (elasticity) and decreasing the mass (inertia) of the system. 2) The amplitude decreases as the natural frequency of the damped vibration increases. 3) The load amplitude is gradually attenuated owing to the $e^{-\frac{\gamma t}{\omega_n}}$ term.

The stress oscillation equation is in good agreement with the FFT analysis result in that it also shows that the load amplitude increases with the strain rate. Here, the load can be assumed to be proportional to the stress because the system is elastic. The three assumptions mentioned in Section 3.1 are in agreement with both the equation and the FFT result. 1) The existence of a natural frequency is confirmed. 2) It is not affected by the strain rate or temperature. 3) It is not affected by the material of the specimen. Theoretically, the material can affect the system because it is also included as part of the system. The mass of the specimen is so small compared with the system mass that its effect on oscillatory response is negligible.

4. Flow Curve Determination

Although oscillation can be attenuated by reducing the weight of the die and increasing its stiffness to reduce the stress wave propagation velocity, there is a limit to the attenuation. Therefore, a better method is simply to eliminate the noisy load oscillating at the natural frequency of the test system, leaving the pure deformation data of the specimen. The noisy load is filtered out by applying a high-pass filtering method, where the cutoff frequency is set to 1500 Hz. Figure 10 shows the stress–strain curves of JIS-S20C obtained before and after filtering.

The non-uniformity and fluctuation of the strain rate due to the acceleration of the main ram in run-up are shown in Fig. 11, and those problems are corrected by using inverse analysis, which uses a specialized thermomechanical FE method to simulate the compression experiment and obtain a uniaxial flow curve.

Moreover, the inhomogeneity of the deformation and temperature distribution owing to internal heat generation and friction is compensated. The distribution data of the temperature and strain using microAVS at the strain rate of 100 s$^{-1}$ and temperature of 1000°C is shown in Fig. 12. The Lagrange multiplier rigid plastic finite element method is applied in the deformation analysis and the Arbitrary Lagrangian Eulerian (ALE) scheme is used for thermal analysis of the specimen and the tool.

The following equation is the constitutive law used for

![Fig. 10. Axial stress-strain curves of JIS-S20C before and after filtering at strain rates of (a) 50, (b) 100 (c) 150, and (d) 200 s$^{-1}$. (Online version in color.)](image-url)

![Fig. 11. Strain rate history of JIS-S20C during compression test. (Online version in color.)](image-url)
inverse analysis to calculate the flow stress:

\[
\sigma = \begin{cases} 
F_1 \varepsilon^n & (\varepsilon \geq \varepsilon_c) \\
F_2 \exp\left[a\left(\varepsilon - \varepsilon_{\text{max}}\right)^2\right] + F_3 & (\varepsilon \leq \varepsilon_c)
\end{cases} 
\]  \hspace{1cm} (9)

Here, \(F_1, n, \varepsilon_c\), and \(F_3\) are independent coefficients that denote the strength coefficient, work hardening coefficient, critical strain, and steady-state stress, respectively. Using the above four independent variables, the three dependent variables (\(\varepsilon_{\text{max}}, F_2, \varepsilon_{\text{max}}\)) can be calculated by the continuity principle at the critical strain \(\varepsilon_c\), matching the zeroth, first, and second derivatives as follows.

\[
F_3 = \frac{F_1 \varepsilon^n - (\varepsilon_{\text{max}} - \varepsilon_c)nF_1 \varepsilon^{n-1}}{1 + (n-1)(\varepsilon_{\text{max}} - \varepsilon_c)\varepsilon^{-1}} \hspace{1cm} (10)
\]

\[
a = \frac{nF_1 \varepsilon^{n-1}}{2(\varepsilon_c - \varepsilon_{\text{max}})} \hspace{1cm} (11)
\]

\[
F_2 = \frac{F_1 \varepsilon^n - F_3}{\exp[a(\varepsilon - \varepsilon_{\text{max}})^2]} \hspace{1cm} (12)
\]

When the strain is smaller than \(\varepsilon_c\), only work hardening and dynamic recovery affect the deformation behavior. Above the critical strain, the deformation of the material undergoes dynamic recovery and dynamic recrystallization, which are reflected in the flow curve as abrupt decreases until the steady-state stress due to the softening mechanism is reached. Its generalized form can be expressed as

\[
\sigma = \bar{\sigma} \left[ \varepsilon^n \exp\left(\frac{A}{1 - \frac{T - T_0}{T_0}}\right) \right] \hspace{1cm} (13)
\]

where \(m\) is the strain rate sensitivity, \(A\) denotes the temperature sensitivity. \(m=0.07(T=800^\circ C), 0.085(T=900^\circ C), 0.1(T=1000^\circ C), A=4360\) are employed.\(^{21}\) This flow curve formulation as a constitutive law represents this metallurgical phenomenon better than the well-known Johnson-Cook\(^{20}\) and Zerilli-Armstrong\(^{21}\) flow stress models. The final result of the flow stress \(\sigma\) obtained by inverse analysis is shown in Fig. 13.

According to Fig. 10, JIS-S20C does not seem to have recrystallized because a decrease in stress due to softening is not observed. Figure 11 shows an increase in strain rate owing to the acceleration of the main ram; Yanagida and Yanagimoto suggested that dynamic recrystallization (DRX) can be impeded by increasing the strain rate.\(^{22}\) That appears to explain why DRX did not occur in Fig. 10. An abrupt increase in strain rate due to acceleration is corrected by inverse analysis and a decrease in stress is shown. Although there is still controversy over whether or not increasing the strain rate accelerates dynamic recrystallization, the above result confirms that the material was partly recrystallized above the critical strain.

5. Conclusion

Through the investigation of the dynamic response of a compression test machine at a high strain rate, the overall process can be summarized as follows.

(1) A compression test using a 15 ton Thermecmaster-Z compression test machine was conducted at strain rates of 1, 50, 100, 150, and 200 s\(^{-1}\). The temperatures used in the test were 800, 900, and 1000°C for JIS-S20C, 380°C for A5083BE-O, and 882°C for Inconel 718. It was found that the oscillation was reflected in the stress–strain curve at a
strain rate of over 50 s\(^{-1}\).

(2) The elastic response of the compression test machine was analyzed. It was found that the Savitzky-Golay filtering technique is better than the 9th-order polynomial and exponential methods for fitting when the deformation is large. From the FFT result, it was concluded that the natural frequency of the testing system is approximately 1 000 Hz and is not affected by the specimen material or test conditions such as strain rate and temperature. However, the amplitude of the frequency is affected by the strain rate, and this result was explained by the stress oscillation equation derived from the SDOF spring-mass-damper model. This result was explained by the stress oscillation equation derived from the SDOF spring-mass-damper model. This proved that the frequency is not affected by the test conditions but by the structural parameters (mass, and stiffness).

The effect of the structural parameters on the natural frequency were proven by Haugou et al. The increase in amplitude with the strain rate is also supported by the equation. The FFT results for other materials (A5083BE-O, and Inconel 718) showed that the natural frequency of the testing system is approximately 1 000 Hz and is not affected by the specimen material or test conditions such as strain rate and temperature. However, the amplitude of the frequency is affected by the strain rate, and this result was explained by the stress oscillation equation derived from the SDOF spring-mass-damper model. This proved that the frequency is not affected by the test conditions but by the structural parameters (mass, and stiffness) of the test machine. The effect of the structural parameters on the natural frequency were proven by Haugou et al. The increase in amplitude with the strain rate is also supported by the equation. The FFT results for other materials (A5083BE-O, and Inconel 718) showed that the natural frequency is the same as that for JIS-S20C, verifying that the observed response was not response from the specimen.

(3) A high pass filter (cutoff frequency of 1 500 Hz) was used to filter out the elastic response, and a stress–strain curve independent of the elastic response was obtained. The flow curve at a high strain rate obtained from this was used to filter out the elastic response, and a stress–strain curve independent of the elastic response was obtained. The flow curve at a high strain rate obtained from this research can be used as valuable data for material genome research, and the author’s research in the future is expected to be continued to obtain material genome at high strain rate.

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