



Analysis of tangential contact damping mechanism by direct observation using X-ray computed tomography

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The damping of metal contact surfaces considerably influences the dynamic characteristics of machines. However, the contact damping mechanism has not yet been sufficiently clarified because it is difficult to directly observe metal-metal contact surfaces. In this study, the deformation of the metal surface asperity caused by a tangential load was analyzed using a combination of X-ray computed tomography and finite element method (FEM) simulations. The FEM simulation considering the elastic-plastic deformation and slip reproduced the experimental results well. The contribution of the elastic-plastic deformation and slip of asperities to contact damping was discussed using the developed simulation.

Damping, Surface, X-ray, Finite element method(FEM)

1. Introduction

The stiffness and damping at metal contact surfaces have a significant influence on the dynamic characteristic of mechanical systems. In particular, contact damping plays a dominant role in the total damping capacity. The design for a contact surface with high stiffness and damping is demanded in terms of industrial applications. However, the contact damping mechanism has not yet been sufficiently clarified although the experimental evaluation of contact damping is a popular research topic [1, 2].

The elastic-plastic deformation and frictional slip of surface asperities have been considered as major contributors to contact damping. An analytical model of contact damping was proposed by considering the elastic-plastic deformation of the asperities [3, 4]. A damping model considering the slip of asperities has also been proposed [5]. However, in these studies, only the damping capacity was evaluated to verify the models from a macroscopic point of view. The deformation mechanism of surface asperities at a micro scale should be clarified for the design of contact surfaces because the elastic-plastic deformation and frictional slip are largely affected by deformation behaviors at a micro scale.

The deformation of surface asperities has been also investigated in conventional studies. For example, the real contact area of the contact surface was evaluated to investigate the frictional sliding mechanism in sheet metal forming [6]. In situ measurements of the real contact area were also conducted using a laser microscope [7] and CCD camera [8]. The distribution of contact pressure was measured to conduct a more detailed investigation on deformation [9, 10]. These studies have provided some valuable results that clarify the deformation of surface asperities. However, most of previous studies only focused on the real contact area. Additionally, the objects were limited to transparent materials, such as polymers and glass, which are often impractical to use in machines.

Furthermore, the hysteresis in the displacement-load relationship should be analyzed to investigate the contact damping mechanism. However, the investigation of this hysteresis

mechanism in asperity deformation is challenging because the hysteresis behaviors largely depend on materials. Thus, the deformation observation of metal-metal contact surfaces is inevitable for understanding the contact damping mechanism although it is difficult using conventional analysis approaches.

In this study, the deformation of the surface asperity caused by a tangential load is analyzed in three dimensions by a combination of X-ray computed tomography (XCT) and finite element method (FEM) simulations. The FEM simulation is used for a detailed analysis of the asperity deformation. XCT enables direct observation of the deformation of metal-metal contact surfaces, which is used to verify the simulation results. The displacement-load relationship is obtained via the simulation to evaluate the energy dissipated in the asperity deformation. The contribution of the elastic-plastic deformation and slip of asperities to contact damping is discussed.

2. Analysis method

2.1. Analysis object

The deformation of the surface asperity on a metal-metal contact surface was analyzed. A schematic of the specimen is shown in Fig. 1. The upper specimen was fastened to the lower specimen by a 150 N vertical preload. Then, the tangential load was applied on

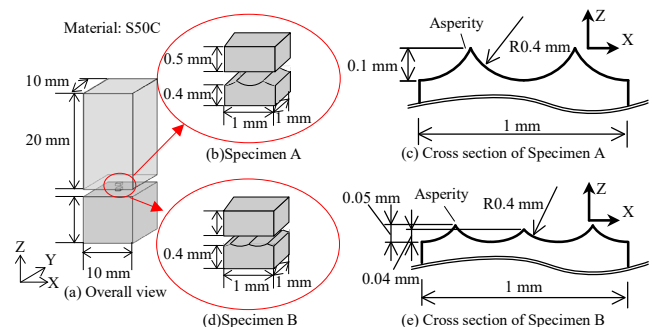


Figure 1. Schematic of specimens.

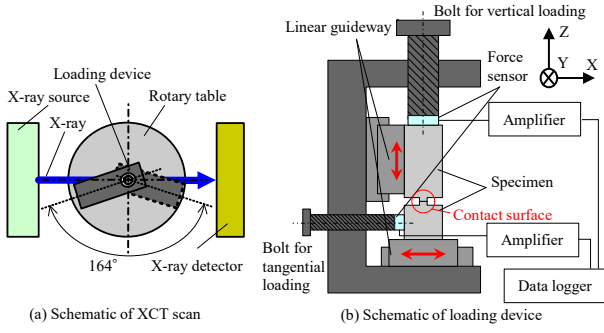


Figure 2. Experimental setup for XCT measurements.

Table 1 Experimental conditions for XCT observation

Vertical preload	150 N
Tangential load	0 N –76 N for Specimen A 0 N –65 N for Specimen B
Number of loading conditions	6
Exposure time	8 s
Number of projections	1201 (One projection per 0.137°)
Pixel size	1.69 μm $\times$ 1.69 μm
Field of view	1698 μm $\times$ 1698 μm
X-ray tube voltage	140 kV

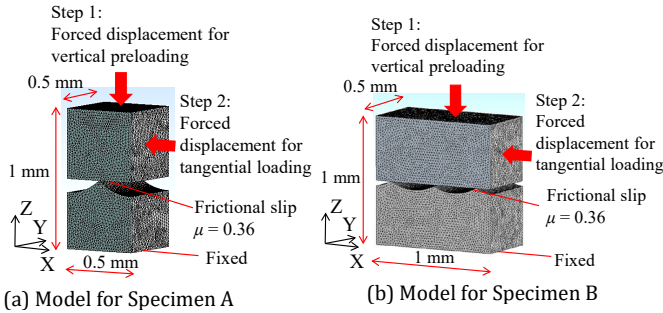


Figure 3. Models in FEM simulation.

the lower specimen. The tangential load was increased stepwise. The transition from the elastic–plastic deformation to the slip of the specimen was investigated by XCT and FEM simulations. The specimen material was carbon steel JIS S50C. The contact surface was cleaned by acetone for measurements under dry conditions.

The upper specimen had a flat surface that was finished by grinding. The lower specimen had cusp asperities that were finished by cutting. Specimen A had two asperities of the same height. Specimen B had asperities with different heights to investigate the micro slip at the lower cusp. The micro slip is a partial slip only at the asperity with a small preload and is assumed to be an important contributor to contact damping.

2.2. Experimental method using XCT

For direct observation of the contact surface deformation, a loading device was developed and installed in the XCT system with a high imaging resolution (ZEISS Xradia 520 Versa). Figure 2 shows a schematic of the experimental setup. The upper and lower specimens were fixed on the linear guideway on the loading device. The vertical preload and tangential load were manually applied using a bolt. The applied load was measured using a piezoelectric force sensor. The sensitivities of the vertical and tangential force sensors were -3.7 pC/N and -4.0 pC/N, respectively.

For XCT scanning under a certain loading condition, the loading device was rotated by 164° about the Z axis using the rotary table of the XCT system. The 3D geometry of the specimen was obtained by reconstruction of projection images. The X-ray penetration direction shown in Fig.2 was selected because the deformation in the XZ plane was focused on. XCT measurement was conducted

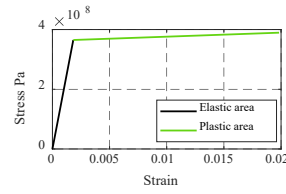


Figure 4. Material properties used in FEM simulation.

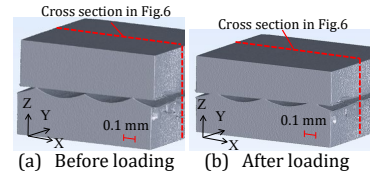


Figure 5. Reconstructed 3D image of Specimen B.

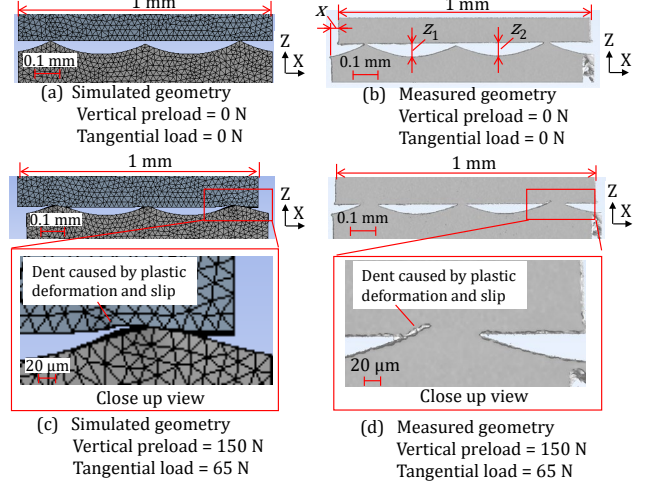


Figure 6. XZ cross-sectional geometry of Specimen B obtained in experiment (red broken lines in Fig. 5) and simulation.

under six loading conditions for Specimens A and B. Other detailed observation conditions are summarized in Table 1. The spatial resolution of XCT measurement can be several times larger than the pixel size. The required resolution is smaller than 5 μm because the observed displacement was smaller than 10 μm in elastic-plastic deformation that is described later in Section 3.2.

2.3. Method of FEM simulation

The deformation of the specimens was simulated via a static structural analysis using the FEM. Figure 3 shows a schematic of the simulation model. Quarter and half-sized models were developed for Specimens A and B, respectively, to reduce the calculation cost. The bottom surface of the model was fixed. The mesh size was set to 20 μm that was the smallest mesh size for convergence of simulation. The vertical and tangential displacements measured in the experiment were applied to the specimen for vertical and tangential loadings, respectively. This displacement was applied to avoid the divergence of displacement in plastic deformation. The vertical and tangential reaction forces were obtained for a comparison with the experimental results. The obtained force was multiplied by four and two for Specimens A and B, respectively, to maintain correspondence with the experiment.

The simplified elastic–plastic material property shown in Fig. 4 was used in the simulation. The elastic modulus was set to 200 GPa. A yield stress of 365 MPa was determined from the measurement results of an indentation test. The frictional slip was set on a real contact surface. Real contact was detected using the program-controlled penalty method. A friction coefficient of 0.36 was set from the measured load after observing the specimen slip using XCT. The FEM software package, ANSYS Workbench 2019 R3, was used in the simulation.

3. Experimental and simulation results

3.1. Asperity deformation

Figure 5 shows the 3D geometry of Specimen B obtained by reconstruction. Figure 6 shows the cross-sectional geometry of

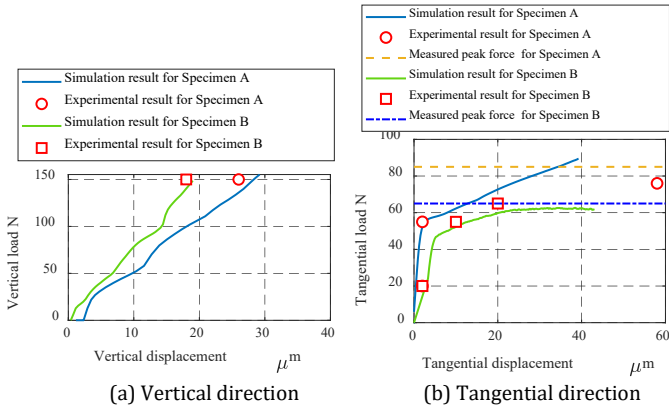


Figure 7. Relationship between displacement and load.

Specimen B along the XZ plane at the specimen center (Fig. 5) obtained in the experiment and simulation. With respect to asperity deformation, the vertical preload first caused the elastic-plastic deformation of the asperity. Then, the tangential load increased the plastic deformation area. Finally, as shown in Figs. 6(c) and (d), a slip occurred between the upper and lower specimens. The dent that was caused by the plastic deformation remained on the upper specimen. The dent geometry is similar in the experiment and simulation. The results in Fig. 6 show that the specimen deformation measured in the experiment is qualitatively well reproduced in the simulation.

3.2. Relationship between displacement and load

The displacement of the specimen in the experiment was obtained from the cross section as shown in Fig. 6(b). The vertical displacement was obtained by averaging the distance values z_1 and z_2 shown in Fig. 6(b). The horizontal displacement was obtained from the distance x shown in Fig. 6(b).

Figure 7 shows the relationship between the displacement and load. In the results for the vertical direction in Fig. 7(a), the simulated displacement-load relationship agrees with the experimental results for both specimens. It indicates that the material property used in the simulation is reasonable.

In the experimental results in the tangential direction in Fig. 7(b), the load increased to approximately 60 N while the displacement was less than 10 μm . The increasing rate of the load is smaller for displacement values larger than 10 μm . It seems that the load will converge to 60 N–80 N. The change in the load-increasing rate indicates the transition from elastic-plastic deformation to slip. This transition in the asperity deformation is also represented in the simulation. The start of the slip in the simulation at a displacement of less than 10 μm corresponds to the start of the slip in the experiment. The final 60 μm displacement in the experimental result for Specimen A is larger than the final displacement in the simulation. The reason for this large displacement is that tangential loading may have continued even after the slip because the load was manually given using the bolt.

A comparison of the simulation results for displacements less than 5 μm in Fig. 7(b) shows that the load-increasing rate is smaller for Specimen B. This indicates the influence of the micro slip at the lower asperity. The contribution of the micro slip is discussed more in detail in Section 4.2.

3.3. Real contact area

The change in the real contact area in the experiment is compared with that in the simulation. Real contact in the experiment was observed in the cross-sectional CT image along the XY plane. Because the cross-sectional image was manually

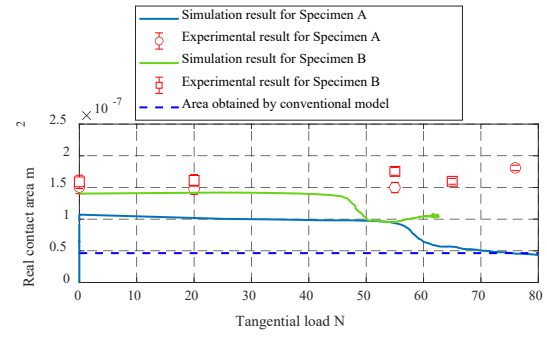


Figure 8. Comparison of real contact area.

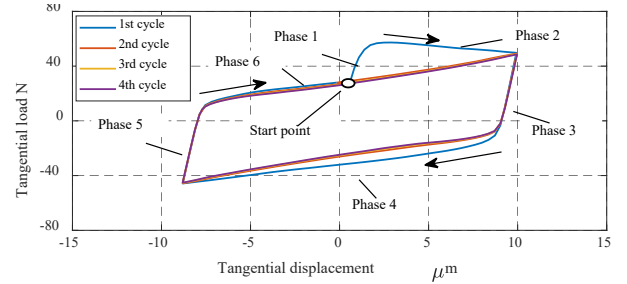


Figure 9. Displacement-load relationship in repeated loading.

selected, the real contact area was obtained by evaluating the scattering and averaging it four times. The real contact area in the simulation was obtained by summing up contact element areas.

The obtained real contact area is shown in Fig. 8. The real contact area obtained using the conventional method that divides the vertical preload by the yield stress is also presented in Fig. 8. The real contact area in the experiment and simulation is 2–3 times larger than the area obtained by the conventional method. The reason for this discrepancy is that the contact of materials with an equivalent yield stress is not considered in the conventional method. In both the experiment and the simulation, both the asperity on the lower specimen and the flat surface on the upper specimen exhibited deformation, as shown in Figs. 6(c) and (d).

In the simulation results, the real contact area decreased at approximately 55 N and 45 N for Specimens A and B, respectively. The reason for this decrease in area could be the forced displacement applied in the simulation. Because the vertical displacement was fixed in the tangential loading, the real contact area decreased owing to the gap caused by the slip and elastic-plastic deformation.

4. Simulation with repeated tangential loading

4.1. Contribution of plastic deformation and slip to contact damping

The tangential displacement-load relationship when a repeated fluctuating load was applied was simulated to investigate the contribution of plastic deformation and slip to contact damping. A simulation similar to the one shown in Fig. 3(a) was conducted. The asperity height was decreased to 50 μm in this simulation. A fluctuating tangential displacement was applied to the specimen in four cycles. The simulation was conducted for displacement amplitudes of 1, 10, and 15 μm . The obtained force was multiplied by four to compensate for the quarter size effect.

The simulated displacement-load relationship for the 10 μm amplitude is shown in Fig. 9. The obtained hysteresis loop indicates that energy is dissipated in the loading cycles. In the first cycle, the deformation can be classified into six phases, as indicated in Fig. 9. First, elastic-plastic deformation occurs in Phase 1. This is followed by the occurrence of slip, and the load slightly decreases in Phase 2. The loading in the opposite direction again causes elastic-plastic deformation in Phase 3. In Phase 4, slip and

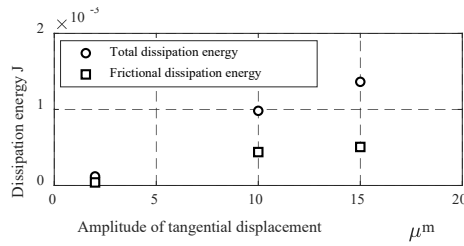


Figure 10. Simulated dissipation energy.

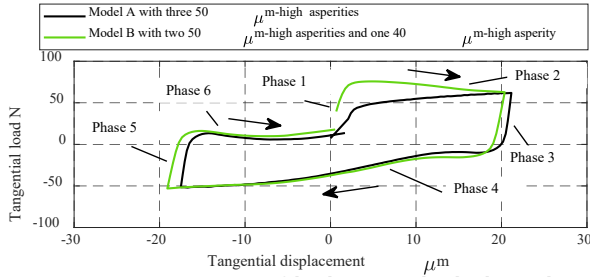


Figure 11. Comparison of displacement-load relationship.

elastic-plastic deformation occur simultaneously. This is because if only slip occurs, the load should not increase in Phase 4. In Phases 5 and 6, the deformation becomes stable and continues into the subsequent cycle.

The displacement-load relationships in the second to third cycles are different from that in the first cycle. This is because the real contact area and vertical load changed due to the elastic-plastic deformation. It demonstrates that the elastic-plastic deformation becomes stable after the second cycle.

To evaluate contact damping, the dissipated energy was obtained by the area of the hysteresis loop in the second cycle. To separately evaluate the contribution of the slip, the frictional dissipation energy was evaluated using the frictional stress and slip distance. The relationship between the displacement amplitude and obtained dissipation energy is shown in Fig. 10. The ratio of the frictional dissipation energy to the total dissipation energy is approximately 40 % regardless of the displacement amplitude. Thus, the contributions of elastic-plastic deformation and slip on contact damping are almost equal.

4.2. Effect of lower asperity on displacement-load relationship

Further FEM simulations were conducted to investigate the effect of the lower asperity on the displacement-load relationship. A fluctuating tangential displacement was applied to Models A and B, which are similar to Specimen B shown in Fig. 3(b). The height of the center asperity of Model A was increased to 50 μm so that three asperities had the same height. The reaction force obtained by Models A and B was multiplied by two because Models A and B are the half-sized models.

The obtained displacement-load relationship is shown in Fig. 11. The dissipation energy of Model B was 22 % larger than that of Model A. This difference is owing to the difference of the tangential load in Phases 1 and 2. The tangential load increased larger for Model B, and the slip occurred at a larger load. The reason for this could be a more severe penetration of the asperity that increases the tangential stiffness and slip load. Compared to the asperities of Model A, the two higher asperities of Model B contacted with larger vertical preload because the preload on the lower asperity was smaller.

The local displacement-load relationship at the asperity top for Model B was obtained and is shown in Fig. 12. For displacement values smaller than 0.3 μm , the load-increasing rate at the lower asperity was smaller than that at the higher asperity. This result indicates that the slip starts earlier at the lower asperity, and the higher asperities bear larger load. Although the slip easily occurs

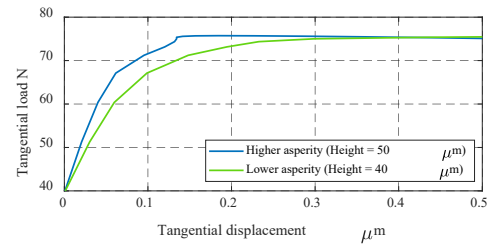


Figure 12. Displacement-load relationship for asperities with different height.

at the lower asperity, the influence of its slip seems small because no significant difference between Models A and B is seen in Phases 3 to 6 in Fig.11.

The results in this section show that the number of contacted asperities and their contact conditions influences the displacement-load relationship. A surface profile design at the micro scale to control the asperity height distribution is expected to be effective in obtaining contact surfaces with high stiffness and damping.

5. Conclusions

The deformation of the surface asperity on the metal-metal contact surface caused by a tangential load was analyzed by a combination of XCT and FEM simulations. The transition from elastic-plastic deformation to slip deformation was well reproduced in the developed simulation. Subsequently, FEM simulations with repeated tangential loading were conducted to investigate the contribution of elastic-plastic deformation and slip on contact damping. The contributions of the elastic-plastic deformation and slip on the contact damping were almost the same for displacement amplitudes of 1 μm –15 μm . The results obtained in this study provide a fundamental understanding of tangential contact damping as well as possibilities for contact damping design. In our future work, the mechanical joint with high stiffness and damping will be designed by controlling the height distribution of asperities.

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