Technical paper

Efforts to Improve Durability of Parts Subject to Earth and Abrasion
- Development of High Hardness and High Toughness Materials, Heat Treatment Technology, and Optimization of Part Shapes -

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In order to extend the life and reduce the size of construction machine parts, materials with higher hardness, strength and toughness are required. We have been developing technology to achieve both hardness and toughness. In this report, we like to introduce the fundamental characteristics of our developed materials and efforts taken for application to parts.

***Key Words**: High hardness, High toughness, Tooth, Improvement in wear resistance, Penetration improvement*

1. Introduction

For construction machinery, since the undercarriage and ground engaging tools (GET) (**Fig. 1**) come in contact with soil/sand and rock-beds, they require high hardness so as not to be worn out. In addition, they must have the required hardness and toughness in order to prevent any cracking and chipping caused by static or impact loads generated during travel or excavation. It is known that, for steel materials, as shown in **Fig. 2**, the toughness has a trade-off relationship with the hardness although the strength is generally proportional to the hardness. For safety reasons, the toughness is secured by lowering the hardness today, but this results in insufficient wear life. If the hardness can be increased while maintaining the required strength and toughness, it will be possible to extend the life or reduce the size of the parts. We like to report that, in a joint study with Osaka University, Sanyo Special Steel, and Komatsu, we managed to develop an alloy content with high hardness (high strength) and excellent toughness and a heat treatment technique[1] by optimizing alloy components of steel and controlling the heat treatment process. We also like to present an application example of high-hardness and high-toughness materials, including our efforts made for developing a tooth aiming at improving customers' life cycle cost (LCC) and production efficiency.

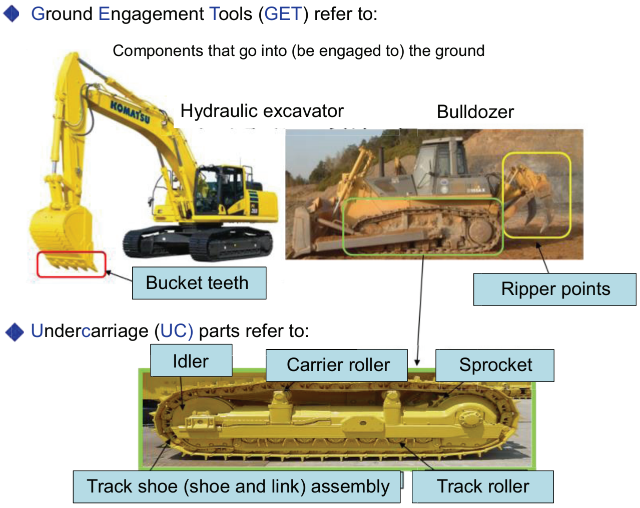


Fig. 1 Outline of undercarriage and GET

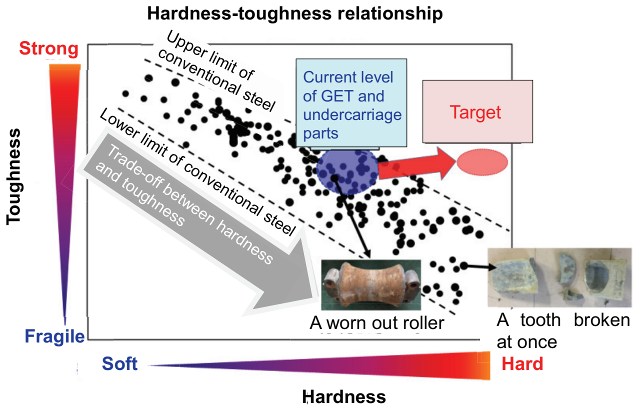


Fig. 2 Relationship between hardness and toughness

2. High-Hardness and High-Toughness Steel

2.1 Conventional Issues and Solutions

The common technique for obtaining high hardness of steel is to obtain a martensite structure by rapidly quenching it from a high temperature at the austenitizing temperature or higher. To obtain a high Vickers hardness of around 700 HV, it is required to use steel with a carbon content of 0.5%C or more. However, ordinary high-hardness steel exhibits a grain boundary fracture or a cleavage fracture along the cleavage plane of crystal (a crack along prior austenite grain boundaries caused by impact load), and its toughness value is therefore low. Particularly for hyper-eutectoid steel having a co-precipitation concentration or more, the carbides on grain boundaries induce a grain boundary fracture as shown in the schematic diagram of **Fig. 3** (a). The steel will also be fragile when quenched from the austenite single phase region to eliminate grain boundary carbides, due to lens formation of martensite caused by coarsening of crystal grain and an increase of solid solution C amount in the matrix (due to disappearance of carbides that played the role of pinning). For high-carbon steel, if grain coarsening is prevented and both the removal of carbides on grain boundaries and the fine dispersion of intragranular carbides are achieved, steel with both high hardness and excellent toughness is expected to be obtained. Thus, we conducted detailed research on the disappearance process of carbide that occurs during hyper-eutectoid steel austenitization and discovered groundbreaking components and heat treatment conditions that can preferentially dissolve carbide on the grain boundary and disappear while leaving intragranular carbides remaining. In addition, effective grain refinement for strengthening and toughening was also achieved concurrently with the heat treatment process, and the microstructure was obtained as shown in the schematic diagram in **Fig. 3** (b). We decided to call this series of grain boundary amelioration and grain refinement processes “Grain Boundary Amelioration (GBA) treatment”.

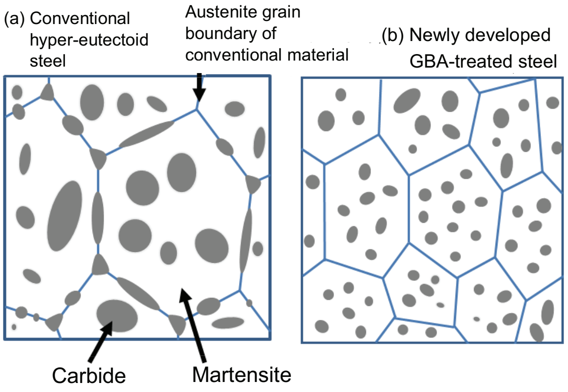


Fig. 3 Schematic diagrams of conventional hyper-eutectoid steel and GBA-treated developed steel microstructures

2.2 Results of Experiments

2.2.1 Microstructure

Appropriate normalizing and spheroidizing annealing were performed on the developed steel with adjusted C, Mn, and Cr amounts of JIS SUJ2 steel, which is commonly used for general purpose bearing steel. Then, the GBA treatment and low-temperature tempering were performed as shown in **Fig. 4.** **Fig. 5**, which shows the resulting microstructure, demonstrates that carbides on grain boundaries are small, a large amount of fine carbides of 1μm or less are dispersed in the grains, and prior austenite grain boundaries are as fine as 4μm or less.

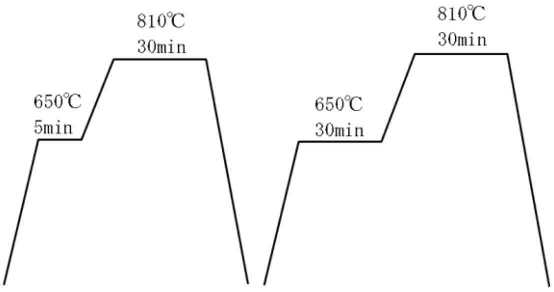


Fig. 4 GBA treatment

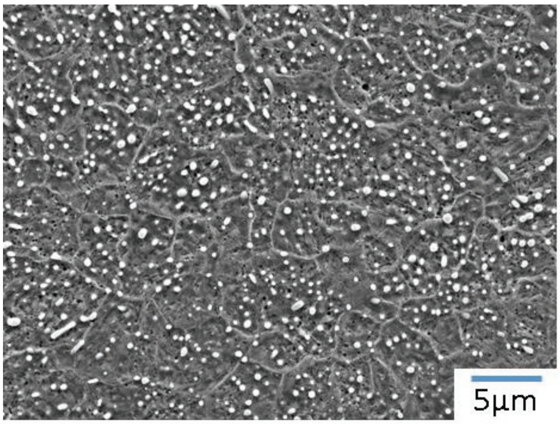


Fig. 5 Microstructure of GBA-treated developed steel

2.2.2 Charpy impact test

Fig. 6 shows the load vs. displacement curve resulting from the instrumented Charpy impact test that was conducted using the 10 RC notch test piece. The displacement up to occurrence of the fracture was larger than that for the conventional high-hardness material, and extremely high impact value was verified despite a high hardness of HRC 60 (approximately 140J/cm^2, which is 5 times or more in the energy). In addition, the macro observation photograph of the fracture surface in **Fig. 7** shows that the developed steel has been deformed largely compared with the conventional high-hardness material. From the micro observation by SEM, it turned out that the conventional high-hardness material resulted in a typical grain boundary fracture, whereas the GBA-treated developed steel exhibited the mode of a ductile fracture with fine dimples. We succeeded in preventing grain boundary fracture by GBA treatment to the developed steel and verified that this developed material is excellent also from the destruction mode.

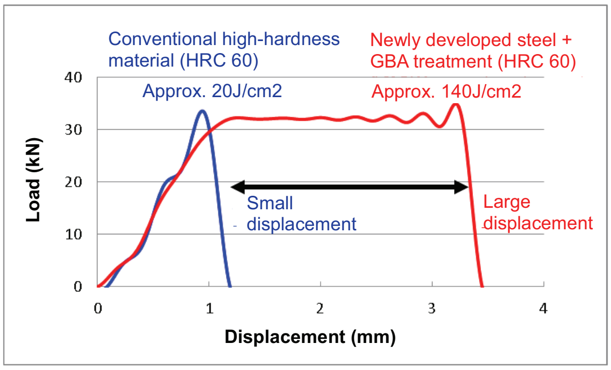


Fig. 6 Load vs. displacement curve resulting from the instrumented Charpy impact test

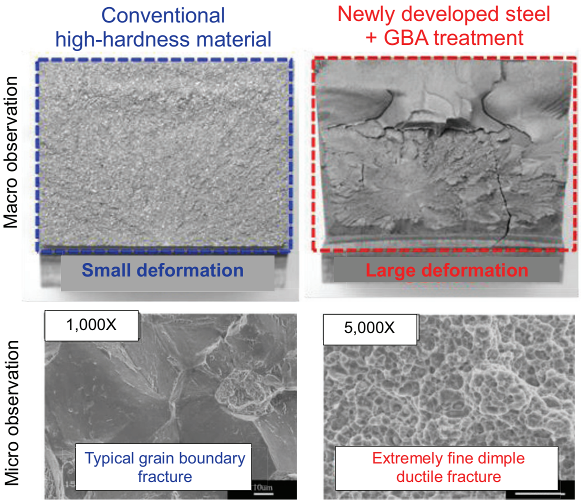


Fig. 7 Observation of impact test piece fracture surfaces

2.2.3 Tensile test

Fig. 8 outlines the tensile test. Because of high-hardness material, we used tensile test pieces as shown in this figure. The test result in **Fig. 9** shows that the conventional high-hardness material fractured during elastic deformation. On the other hand, the GBA-treated developed steel yielded before deforming and fracturing. Its fracture displacement was 5 mm or more, while the fracturing load was as high as 2,400 MPa.

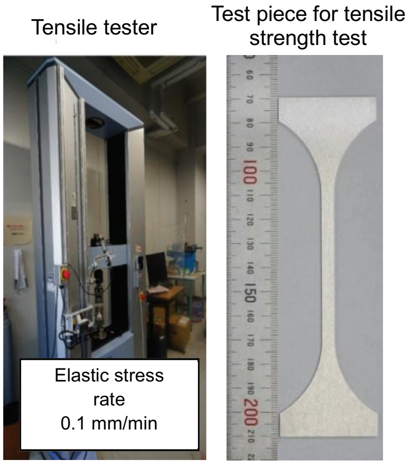


Fig. 8 Outline of the tensile test

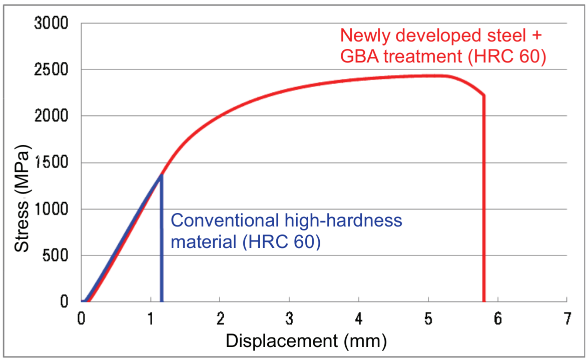


Fig. 9 Result of the tensile test

2.2.4 Bending test

The developed steel is assumed to be used for ripper points used on bulldozers, which works like a hoe used to plow the ground before land leveling. The bulldozer travels while sticking the ripper points into the ground. For this reason, we conducted a bending test in order to evaluate the breakage of ripper points. **Fig. 10** outlines the bending test, and **Fig. 11** the result. Like the tensile test, the conventional high-hardness material fractured before yielding, whereas the GBA-treated developed material deflected by approximately 10 mm after yielding and the fracture stress was as high as 4,500 MPa or more.

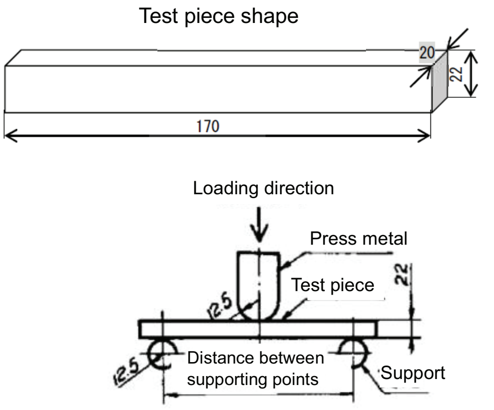


Fig. 10 Outline of the bending test

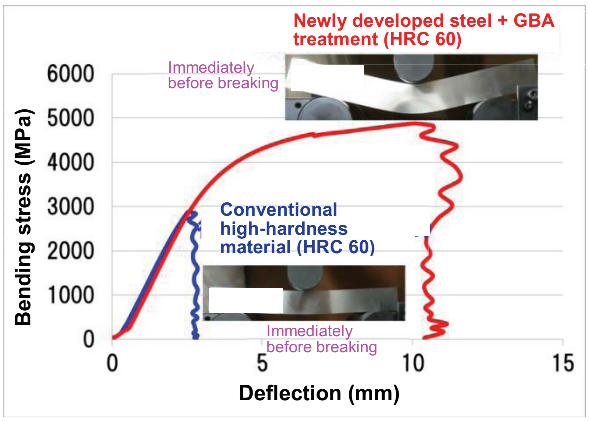


Fig. 11 Result of the bending test

3. Case Studies on Developing DANTOTSU Parts by Utilizing High-Hardness and High-Toughness Steel Long Life Tooth and High-Penetrability Tooth

3.1 Development of Long Life Tooth

The bucket tooth, attached to the tip of the bucket as shown in **Fig. 12**, comes in contact with rock and soil/sand during excavation, therefore requiring high abrasion resistance and toughness. For the conventional tooth, in order to secure the toughness and reduce the breakage risk, the hardness is lowered to balance the abrasion life and breakage resistance. To overcome this situation, a tooth with less breakage and excellent abrasion resistance can be realized by applying the high-hardness and high-toughness steel to the tooth.

Fig. 12 Bucket tooth

Fig. 13 shows the result of a long life tooth prototype manufactured by applying the above-mentioned high-hardness and toughness material. It demonstrates that both the hardness and toughness for the long life tooth improved compared with the existing tooth.

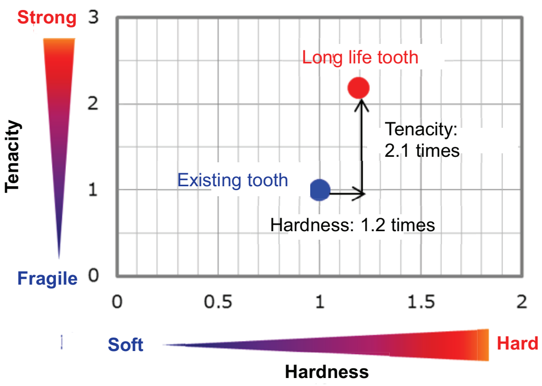


Fig. 13 Results of the actual machine test for the long life tooth

We evaluated the lifetimes of this long life tooth and the existing tooth using an actual machine. **Fig. 14** shows the result. The times up to a certain identical tooth abrasion life were evaluated as the lifetimes, which showed that the wear life of the developed tooth was about 1.8 times that of the existing tooth.

In addition, there were no trade-offs to hardness increase (i.e. no breakage or chipping).

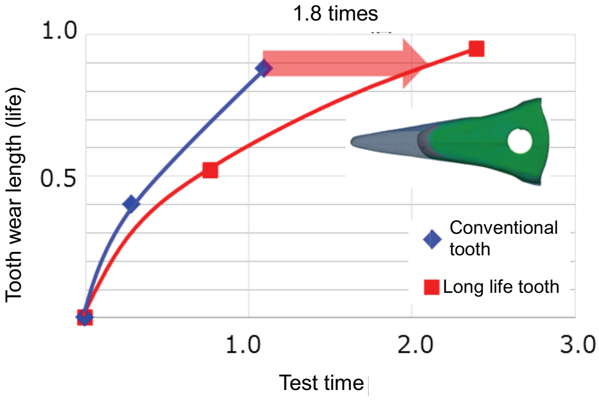


Fig. 14 Results of the actual machine test for the long life tooth

3.2 High-Penetrability Tooth, User Productivity Improvement

Bucket teeth are indispensable parts for efficient excavation of rock and soil/sand and require the appropriate penetrability to improve the excavation efficiency and the increase of fuel economy. Because of its abrasion life and breakage risk, the conventional tooth has large restrictions on its shape. To overcome this, it is possible to realize a tooth with an abrasion life that is equal to or greater than the conventional one even if it is formed into a thin and high-penetrability shape by utilizing the high-hardness and high-toughness features of the developed material (**Fig. 15**).

	Shape of existing part		Shape of high-penetrability part
Shape			
Material	Existing material	High hardness and high toughness	High hardness and high toughness
Currently used			
Characteristics	Conventional tooth	Long life	Long life and High penetrability

Fig. 15 Outline of the high-penetrability tooth

First, a tooth shape with the high penetrability was searched for by using a robot and resin tooth models made with a 3D printer. In the test, as shown in **Fig. 16**, a load cell and tooth resin model were attached to the robot, and the difference in resistance of the tooth inserted into the gravels was evaluated as the penetrability index. In order to examine the factors influencing the penetrability, the evaluation was conducted using multiple tooth resin models with varied tooth tip widths, total lengths, and sectional areas (**Fig. 17**).

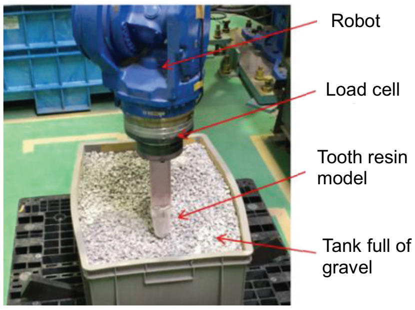


Fig. 16 Scene of the robot simulation test

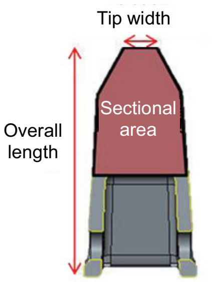


Fig. 17 Shape evaluation items

Fig. 18 shows the results of the robot simulation test. As shown in the figure, there is a high correlation between the tooth tip width and the penetration resistance, and it turned out the penetration resistance tends to decrease as the tip is thinner.

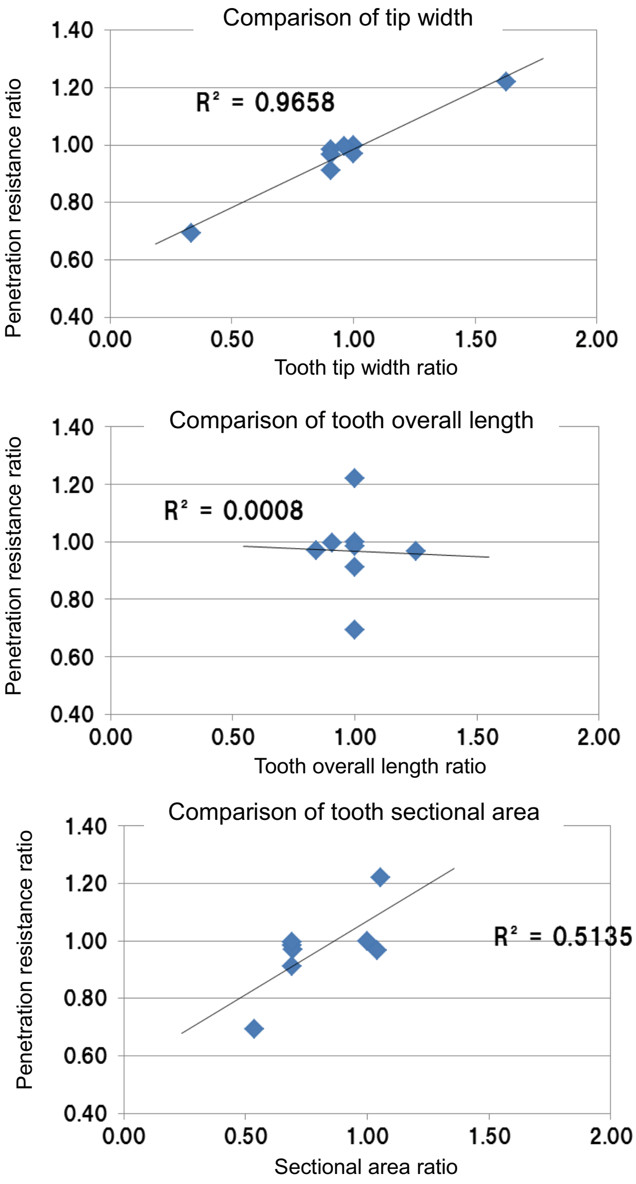
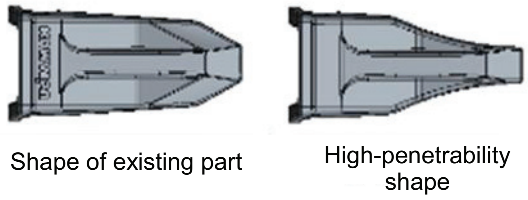


Fig. 18 Results of the robot simulation test (shape factors and penetration resistance)

We devised a tooth shape with a thin and sharpened tooth tip based on the results of the robot simulation tests (**Fig. 19**). Regarding the devised model, after the tooth was penetrated, by the robot several thousand times into the gravels, the penetration resistance of the worn out tooth was compared and evaluated. **Fig. 20** shows the results. Since the high-penetrability shape has a low penetration resistance also after the tooth has worn out, it can be expected to reduce retrying of excavation needed when the tooth fails to stick into the ground. Consequently, the workability and the user's productivity are expected to improve.


Shape of existing part

High-penetrability shape

Fig. 19 Tooth with high-penetrability shape

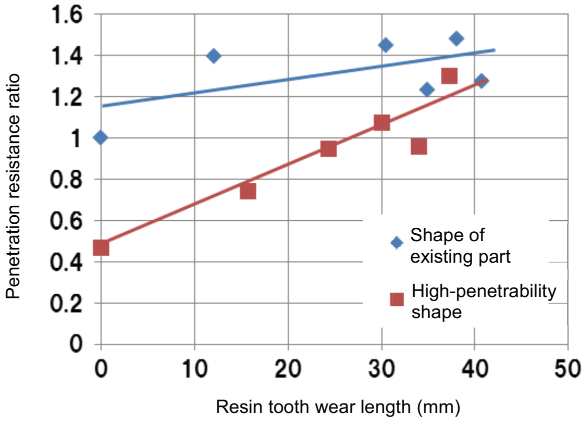


Fig. 20 Change in penetration resistance for a worn out teeth

From now on, we will evaluate the penetrability, durability, and abrasion life on an actual machine using tooth prototypes we made (**Fig. 21**).

Fig. 21 High-penetrability tooth prototype

4. Conclusion

The following is the summary of the results obtained in the development and research in this report, "Efforts to Improve Durability of Parts Subject to Earth and Abrasion":

(1) By GBA treating the developed steel, we have succeeded in controlling grain boundary carbides that cause grain refinement and embrittlement and have improved the

toughness by at least five times that of the conventional high-hardness material. In addition, through the tensile and bending tests, we verified substantial improvement in the displacement as compared with the conventional high-hardness material.

(2) We applied the developed high-hardness and high-toughness material to bucket teeth and verified that our actual-machine test did not cause any tooth breakage and the abrasion life extended by 1.8 times of that of the conventional material.

(3) Through our development of the tooth of high-penetrability shape, we confirmed that it would reduce the penetration resistance to sandstone during excavation. Consequently, the workability in excavation, fuel economy, and productivity of users are expected to be improved.

References

[1] Yoritoshi Minamino, Junichiro Suzuki, Kimitoshi Nakamura, Yusuke Hiratsuka, Norimasa Tsunekage, Koji Yamamoto, and Kazuo Miyabe: CAMP-ISIJ, 29(2016), 754

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[A comment from the authors]

We consider that the purpose of the developed new material is not only to prolong the service life of parts but also to create more value-added DANTOTSU products by changing the structure taking advantage of the characteristics of the material. We will continue to work on technology development to allow the material to be applied not only to the cases introduced here but also to various other parts.

We would like to express our sincere gratitude to Professor Minamino and students of Osaka University for implementation of the industry-academia collaborative joint research.