Sample Size Effect on the Impact Absorbed Energy in Carbon Steel With Different Microstructures

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INTRODUCTION

Charpy impact test is the traditional testing method which was developed at the early 20th century. This test has been conducted with the specimens with the V- or U- notches which have primitive difference to the conventional fracture mechanics tests in their stress conditions. This means the difficulty to apply the Charpy impact test simply to determine the parameters necessary for the study based on the fracture mechanics. However, due to its convenience and long history, the Charpy impact test still has been adopted for the preliminary examination of toughness and the extended application can be found in the recent studies.

One of the extensions is the miniaturization. Kimura et al. 1 has developed one of the miniaturized impact testers that makes possible to extend the application of Charpy impact test to the local part of products, for example the each parts (weld metal, heat affected zone) of the welding joint which has limited volume preventing from cutting of the standard size Charpy test pieces. According to their work, the absorbed energy at room temperature can be estimated with any specimen size if the ductile fracture takes place. On the other hand, it is well known that carbon steel is able to consist of different microstructures such as pearlite, martensite, ferrite and bainite. These microstructures exhibit different morphologies. Some of these have anisotropy in these shape as well as the mechanical properties represented by elastic modulus and yield stress. These differences bring

Figure 1. Thermomechanical processes to prepare different microstructures. Pearlite (a), tempered martensite (b) and bainite (c). The caliber rolling was adopted to evolve the directionally elongated pearlite.

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different stress field around the crack tip and thus the change of the sample-size effect on impact fracture is predicted. Although there are some reports about this size effect with different steels\textsuperscript{2,3}, the experimental data adequate for the estimation of the standard size Charpy absorbed energy with different small specimens has not been found. This study is aimed to clarify this sample size effect with the high carbon steels having different microstructures while with the same chemical composition.

**EXPERIMENTAL PROCEDURES**

A SAE9254 spring steel (0.53%C-1.48%Si-0.76%Cr-0.70%Mn-bal.Fe, JIS-SUP12) was examined. The spring steel has enough hardenability\textsuperscript{4,5} to obtain different microstructure with different thermomechanical processes as shown in Fig.1. Pearlite was obtained with the bar having a diameter of 40 mm by austenitization at 850 °C for 30 min at the electric box furnace followed by air cooling (Fig.1a). Additionally, the caliber rolling\textsuperscript{6,7} was adopted to some of the pearlitic steels to evolve the elongated morphology. The rolling was conducted to obtain a cross section of 14 mm square (a total reduction in cross section of 84 \%) at room temperature. The lubrication was applied on the sample surface to reduce rolling load. Tempered martensite was prepared by austenitization at 1100 °C for 15 min, water quenching followed by tempering at 600 °C for 30 min (Fig.1b) with electric box furnace. Additionally, bainite was fabricated by austempering at 400 °C following the
austenitization at 850 °C (Fig.1c). It should be noted that the spring steel contains significant amount of Si and thus the precipitation of carbide was suppressed and austenite retained by the austempering.

Tensile test was conducted at room temperature with the specimen having a dimension with a gage diameter of 6 mm and a gage length of 30 mm. A constant cross head speed was 0.85 mm/min. The tensile direction for the rolled pearlite was parallel to the rolling direction (RD). Impact test was conducted with conventional Charpy impact test as well as the miniaturized impact test. Charpy impact test was examined with standard size specimen with a cross section of 10 mm square and 45 ° V-notch with an instrumented hammer at room temperature. Miniaturized impact test was conducted according to the method developed by Kimura et al. The sample was set on the anvil with a gap of 13 mm and strike by an instrumented tup with a tip radius of 1 mm, as shown in Fig.2. Three shapes of specimens with a cross section of 2x2, 1.5x1.5 or 1x1 with 45 ° V-notch were examined at room temperature at a strike speed of 3 m/sec. The impact energy was examined by the load-displacement curves.

Microstructure and fracture surfaces were observed by a scanning electron microscope (SEM, JEOL 7000F) operated at an accelerated voltage of 15 kV. Surface for the microstructural observation was prepared by mechanical griding followed by electro-polishing.

RESULTS AND DISCUSSION

Figure 4 shows the SEM microstructures of the spring steel with pearlite (a), rolled pearlite (b), tempered martensite (c) and bainite (d). The pearlite (a) consists of several colonies in which the elongated direction is almost identical and lamellar.

Figure 4. SEM microstructure of the spring steels with pearlite (a), rolled pearlite (b), martensite tempered at 600°C (c) and bainite consisting of bainitic ferrite and retained austenite (d).
spacing appeared around 100 nm. The caliber rolling of pearlitic steel changed the elongated direction of lamellar structure to the RD and fine lamellar structure with a spacing of a few tens nm was evolved at dominant part, while some of the colonies shows irregularly bent lamellar morphology, as shwon in Fig.3(b). These morphology is able to be found in a drawn wire and cold-rolled pearlitic steel. The tempered martensite shows lath-martensite with globular cementite whose diameter is around 100 nm (Fig.4c). The bainite consists of bainitic ferrite and retained austenite. The area fraction of austenite was 40 % which is similar to the high carbon steel bainite previously reported. Although all of these contains an elongated character, only the rolled pearlite has macroscopical anisotropy of morphology with respect to mechanical coordination.

Figure 5 shows the nominal stress–nominal strain curves of the spring steel with different microstructures shown in Fig.4. The pearlite shows relatively low strength while the rolled pearlite shows high tensile strength of 1.5 GPa with large post-
uniform elongation with necking. The yield stress of the tempered martensite shows 1.0 GPa and tensile strength of 1.2 GPa was appeared after the work hardening with uniform elongation of 8%. The bainite shows significant large uniform elongation of 34% which is mainly due to the deformation-induced martensitic transformation or so-called TRIP (Transformation Induced Plasticity) effect.

The load – displacement curves obtained by the Charpy impact test with 10x10 standard size specimen was shown in Fig.6. All four microstructures show maximum load at the early stage of deformation followed by gradual decreasing. All of the samples were fractured by ductile manner. The pearlite and the bainite show low maximum load with short displacement keeping adequate load. The low toughness is well known as a weak point of pearlite 12. The tempered martensite shows the better properties. The notable toughness was found in the rolled pearlite which shows both the largest maximum load and longest displacement keeping adequate load. The macroscopic appearance of fracture surfaces shaped large separations elongated to the RD, the morphology similar to which was reported the deformed martensite with elongated morphology 6.

The toughness of the rolled pearlite characteristically different from the other microstructure was found in the miniaturized impact tests as shown in Fig.7, where the load – displacement curves measured by the different small specimens were presented. The pearlite (a) and the bainite (d) showed the gradual increasing of the load after the onset of the plastic deformation, while the rolled pearlite (b) and the tempered martensite (c) did not show the clear increase. These differences indicate the differences in both initiation and growth of crack among these microstructures. The rolled pearlite (d) shows the largest displacement with keeping impact load among all the microstructures at any size of the specimen. This means that the rolled pearlite indicates the most preferable absorbed energy at the miniaturized impact test as well.
Figure 8 shows the specimen size effect on the maximum load (a) and the absorbed energy (b) of all the microstructures. The larger maximum load was detected with the microstructure having higher tensile strength at any size of the specimens. The relationship between the maximum load and the specimen size is able to be regret by power law relationship when the sample size is limited to the miniaturized impact test specimens. In other words, the maximum load with the standard size specimen (10x10) shows deviation at lower side from that calculated by the extrapolation with the regression for the miniaturized impact test. The reason for this deviation has not been clarified yet. However, the possible reasons should be the difference in the geometry of test system arrangement such as the gap of specimen support, as well as the difference in the plasticity and the fracture behavior. The relation between the absorbed energy and the specimen size (b) is able to be represented with power law relation covering both the standard size Charpy test and the miniaturized tests. The slope of the elongated pearlite shows larger than those of the other microstructures, indicating that the specimen size effect has the dependence on microstructure.

As shown in the microstructures in Fig.4, the elongated pearlite has the anisotropic morphology in which the lamellar structure is elongated perpendicular to the impact direction. This morphology brought the characteristic fracture surface as shown in Fig.9. When the specimen size is relatively large, such as the 2x2 specimen (a), the fracture surface includes some large separations extended in different directions. On the other hand, the specimen with the smaller size shows the less number of separations. This change was not observed in the other microstructures. Consequently, the separation appears related to one of the possible mechanisms to bring the difference in the specimen size effect.

In order to examine the specimen size effect with the different perspective, the absorbed energy normalized by the ligament area (the area between the notch-tip and the opposite surface) is shown in Fig.10. While the spring steels with the relatively low strength (the pearlite and the bainite) has no significant dependence of the specimen size, the spring steel with the higher strength shows the tendency that the area-normalized absorbed energy becomes smaller. The size effect similar to that for the rolled pearlite was found in the previous study reported by Lucon et al. Figure 10 indicates the upper shelf energy of the tempered martensitic steels (AISI4340, X70) with the standard size and the sub size specimens. Although no data for the impact energy measured by miniaturized impact test with V-notched specimen having square cross section were found, the common feature among the reference data and this work for the relatively large specimens indicates the mechanism for the size effect other than that related to the separation. As mentioned with Fig.7, all the fractures in this work appeared ductile manner, and thus the absorbed energy was consumed partially for the plastic deformation. Miyazaki et al. reported, in their work on the tensile tests, that apparent yield stress decreases when the specimen thickness is smaller than 5 to 10 times larger mean grain size for several metals including iron. This knowledge indicates the possible tendency that the specimen thickness effect on
yield stress appears stronger when the yield stress is larger. However, the results in this work would appeared different tendency if the toughness were controlled only by the yield stress. This indicates that the significant size effect with the rolled pearlite should be due to the several mechanisms including unknown one so far.

**CONCLUSIONS**

Specimen size effect on the absorbed energy at impact fracture of the spring steel (0.53wt%C-1.48%Si-0.76%Cr-0.70%Mn-Fe) with different microstructures was studied. The pearlite, rolled pearlite, tempered martensite and bainite with retained austenite were prepared by the different thermomechanical processing. The impact test was conducted at room temperature with V-notched specimens having different cross-sections (standard: 10x10, miniaturizing: 2x2, 1.5x1.5, 1x1). The rolled pearlite shows preferable toughness at any specimen size while the miniaturizing of the specimen size for the rolled pearlite shows larger decrease in the area-normalized impact energy. This significant size effect is probably due to the anisotropic morphology as well as other plastic properties.
Figure 10. Area-normalized absorbed energy of the spring steels with different sizes of the specimens. The absorbed energy was normalized by the area of the ligament part under the notch-tip. The reference data of the upper shelf energy of different steels reported by Lucon et al. was illustrated as well.

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REFERENCES


