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USE OF FEMTOSECOND LASER TECHNIQUE FOR STUDYING PHYSICALLY SMALL CRACKS

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Abstract. Since small crack propagation behavior is strongly affected by microstructure, very small artificial notches with a length in the submillimeter range are needed for a systematic study of microcrack behavior. Laser processing technique with ultrashort pulses is a micromachining tool which will not cause any serious mechanical damage in metallic materials. Small artificial starter notches were manufactured in medium carbon steels with this technique and some fatigue tests were carried out. Laser affected zones could be observed at the notch boundary but cracks were initiated from the notch tips and propagated steadily. The crack paths were very tortuous like natural small cracks. The experimental results showed that the femtosecond laser processing technique is useful to introduce a small notch and allows systematic investigation of microcrack behavior.

Keywords: femtosecond laser, physically short crack, laser micromachining, small notch, fatigue

Introduction. It is well known that microcrack growth behavior is strongly affected by the microstructure (e.g. Miller, 1982, Suresh and Ritchie, 1984, Tokaji et al., 1986). Since fatigue life of a structural material is dominated by small crack propagation, it is important to understand the small fatigue crack growth behavior. In the regime of physically small cracks (Suresh and Ritchie, 1984), the fracture mechanics similarity principle is violated, but crack extension behavior can be analyzed by some continuum mechanics based approach. Whereas experimental procedures to determine crack growth curves are readily available for long cracks, similar methods have yet to be developed for physically small cracks. One of the

basic problems is to define starter notches from which physically small cracks can be initiated in a well-defined way. A very small mechanically drilled hole (Murakami et al.) or an electro-discharge machining pit (Kruzic et al. 1998) have been used as a starter notch to investigate the small crack behavior. These methods are, however, not useful when the correlation between the crack orientation and the strongly anisotropic microstructure is investigated because the crack starting point cannot be predicted with a circular hole. A small notch with a well-defined shape is needed for a systematic study for the behavior of physically small cracks. Microfabrication techniques which have become available over the last few years allow a more precise preparation of micronotches. One method is the focused ion beam technique which can be used (Marx and Vehoff 2005) to place micronotches in the vicinity of grain boundaries. Problems associated with this method are contamination by foreign atoms and very long machining times.
Femtosecond laser (fs-laser) machining technique is another microfabrication tool. A femtosecond laser has very short pulses in femtoseconds (1 fs = 10^{-15} s), whereas conventional lasers which are used for cutting or welding materials have pulse durations in the range of longer than nanoseconds, like excimer lasers or Nd:YAG-lasers. They cause thermal or mechanical damage in metallic materials such as melting, forming of burr or changes in the morphology. This effect can not be neglected especially when they are applied to the microfabrication. In contrast, the fs-laser machining hardly damages the surrounding area mechanically and seems to be a promising candidate for the precise micromachining of metallic materials (e.g. Luft et al., 1996, Wellershoff et al., 1999). With this method crack-like small notches of pre-defined shape can be machined, for example a notch inclined at a certain angle to the loading direction. A first attempt to use laser processing technique to study microcrack propagation is described this paper. Some artificial notches are fabricated in the medium carbon steel, and fatigue crack propagation behavior from the notches is observed. The usefulness of the femtolaser machining in studying physically small cracks is discussed on the basis of the results.

Femtosecond laser machining. Since the femtosecond laser has the much faster energy deposition, its ablation process and effect on the material is different from that with the long-pulse (nano- or microsecond) laser. The ablation with the fs-laser takes place in the vapor and plasma phases, whereas the long pulse ablation occurs in the liquid and vapor phases. The long pulse laser induces heat diffusion out of the irradiated area. The large surrounding area of the treated place is affected by heat during the process for materials with high heat conductivity. This leads the material melting and resolidification if the material has low melting temperatures. With the fs-laser, the laser radiation is absorbed in the surface layer of the material and little heat diffusion occurs. Because the treated medium is transformed directly into the vapor and plasma phases, shockwaves which induce mechanical stress are reduced. Consequently, the surrounding area which is affected either thermally or mechanically with the fs-laser processing becomes much smaller than the one with the long pulse laser processing. This advantage of the fs-laser technique has been proved by its application to cutting explosives for which neither shock waves nor thermal energy are acceptable (Perry et al., 1999). More technical details of the laser microfabrication technique are described elsewhere (Nolte, 2003).

Figure 1 shows the schematic illustration of the laser processing system used in this study. Ultrashort pulses with a duration of femtoseconds are generated by a Ti-sapphire fs-oscillator and a CPA-amplifier. The excited fs-laser is led through a modified microscope to a sample. The mirror inside the microscope is pivoted so that it can be work as an optical microscope which is used to decide the target point to be processed. 3D positioning of the sample is controlled by three step motors combined with a piezo-stage. The accuracy of this stage is less than 10 nm in all three axes and total translation in each axis is several centimeters. The positioning system and the laser unit are controlled by a PC-unit.

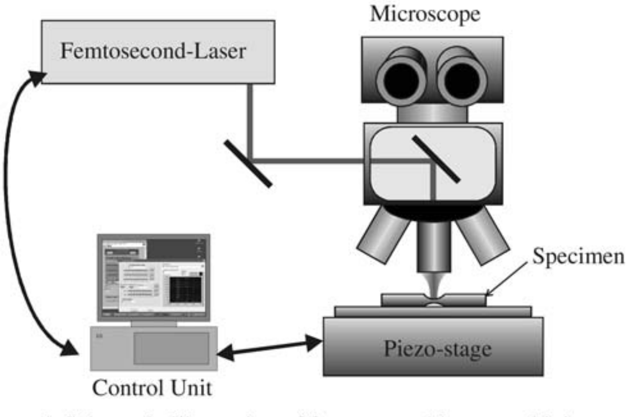


Figure 1. Schematic illustration of femtosecond laser machining system.

Some small notches were manufactured in a medium carbon steel (AISI 1045) with the fs-laser technique whose parameters are listed in Table 1. A target shape of the notch was a semiellipse with a length of $2c$=100 μm and a depth of a=20 μm so that the aspect ratio of the notch is a/c<1. The laser processing trace can be programmed. In this study it was set to be spiral and the piezo stage moves according to the programmed trace. The maximum mouth size in the middle of the notch should be ideally as small as possible to simulate a natural crack, but it was set to have the ratio of 0.2 to the whole length $2c$ of the notch in order to achieve the target depth. The resultant notch was seen narrow ellipse on the surface. Three different types of notches were created. One was a single notch lying perpendicular to the loading axis, another was a single notch inclined to the loading axis by 45° and 60° respectively to simulate mixed mode crack propagation. The last one had two adjacent notches for multicrack interaction simulation. A top view of the obtained single notch is shown in Fig. 2. The target sizes on the surface agree well with the obtained dimensions of the notch.

Table 1. Parameters of femtosecond laser.

Pulse length : τ	50 ± 10 fs
Wave length : λ	800 nm
Energy : E	0.2 ± 0.02 μJ per shot
Focal spot diameter	1.4 ± 0.4 μm
Fluence : F = E/Area	5.5 J/cm^2

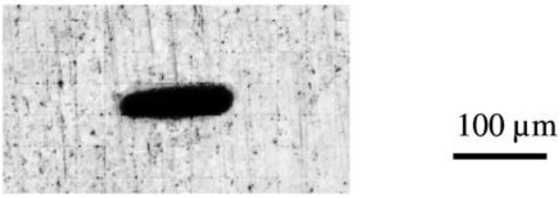
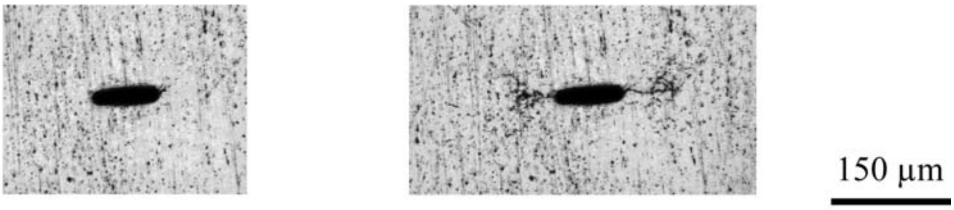


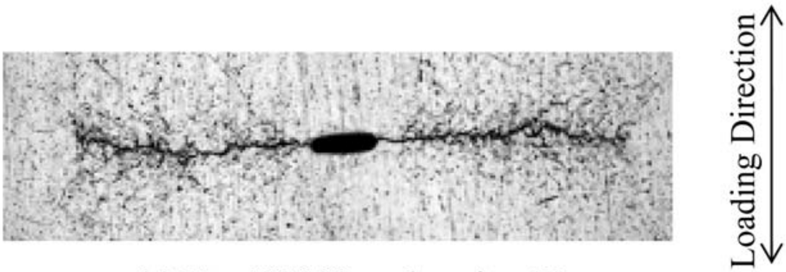
Figure 2. Single notch machined by femtosecond laser.

Experiments and Results. Fatigue tests were carried out under fully reversed push-pull loading with a constant amplitude. The tests were interrupted at every 20000 cycles and crack propagation behavior from the artificial notches was observed with a long distance microscope. Figure 3 shows the crack growth from the single notch. Natural cracks were initiated from the tips of the notch and grew macroscopically perpendicular to the loading direction. The microscopic crack path was, however, very torturous as a result of a great amount of kinking and branching at a microstructural level. It was also observed that the damage area expanded radially around the crack as the crack length increased. The crack propagation behavior from the 60°-tilt notch and the multiple notches are shown in Figs 4 and 5, respectively. In all cases, natural cracks were initiated from the notch tips and propagated kinking microscopically. Crack coalescence was observed in the multiple notches case. Figure 6 shows the macroscopic change of the crack increment at every 2000 cycles after the natural crack was initiated from the both tips of the notch. The extension rate increased gradually in each case and before the final fracture the cracks extended rapidly. The multiple notch case showed deceleration of crack expansion after crack coalescence on the surface. This is related to the fact that a shallow crack extends more rapidly in depth direction than on the surface.



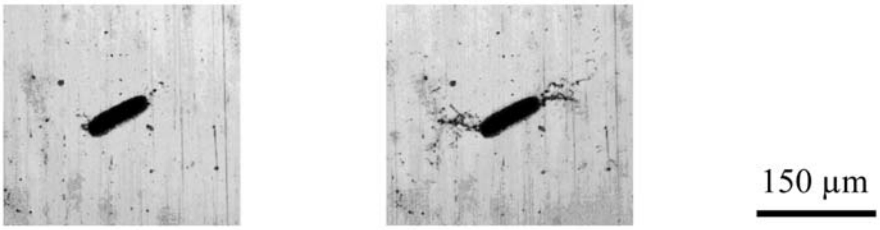
(a) Natural crack initiation from the notch

(b) N = 60000 cycles after (a)



(c) N = 100000 cycles after (a)

Figure 3. Crack propagation behavior from a single notch.

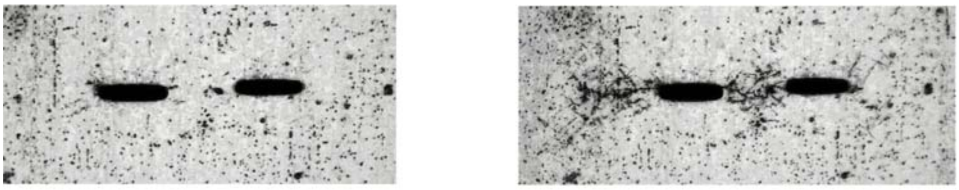


(a) Natural crack initiation from the notch

(b) N = 60000 cycles after (a)

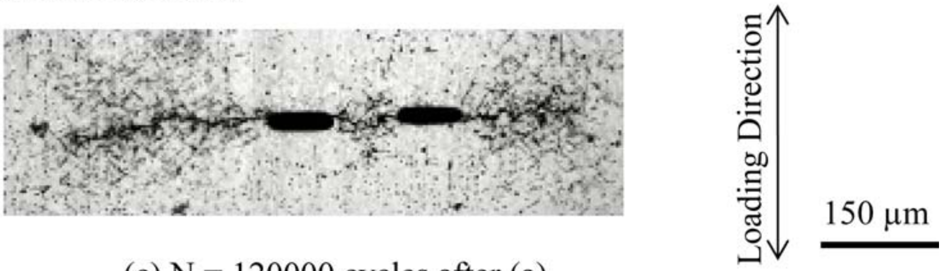
(c) N = 100000 cycles after (a)

Figure 4. Crack propagation behavior from a tilt notch.



(a) Natural crack initiation from the notch

(b) N = 100000 cycles after (a)



(c) N = 120000 cycles after (a)

Figure 5. Crack propagation behavior from multiple notches.

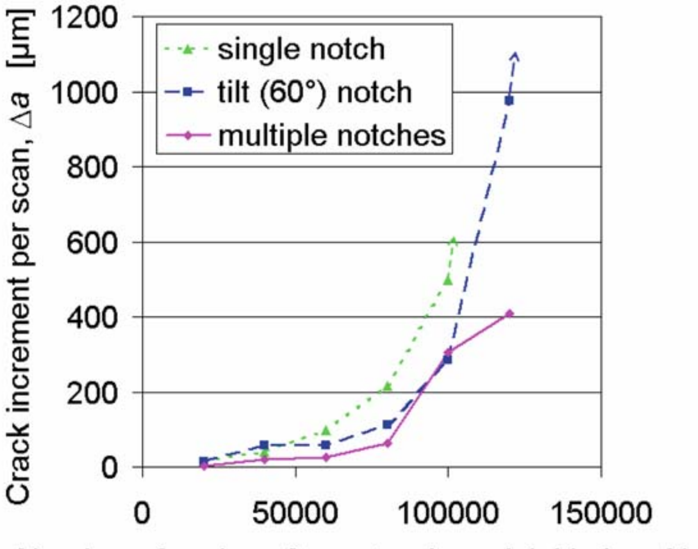
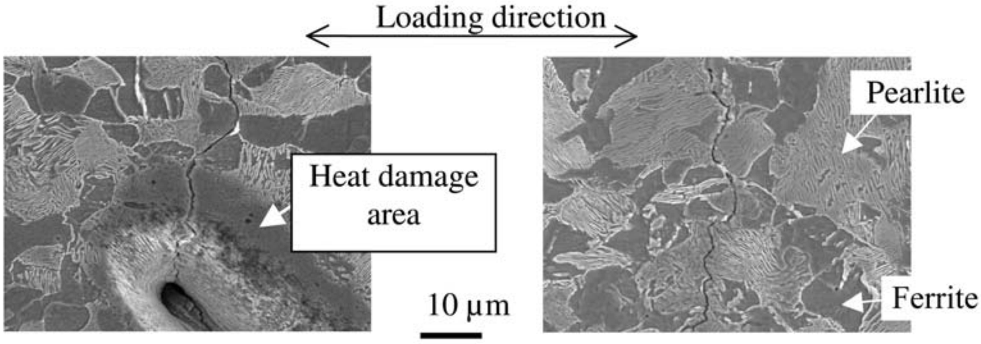


Figure 6. Crack increment change at every observation.

Figure 7 shows the SEM pictures on the etched sample with the 45°-tilt notch after the fatigue test. The material used has pearlite / ferrite dual phase structure. The crack path started from the notch root. A laser affected zone was observed around the notch hole where the microstructure was damaged, which was formed by heat diffusion during laser processing. It was non-symmetric with respect to the notch with a maximum size of about 10 μm in width on the surface. This could be caused either by problems with the accuracy of the translation stage or by the instability of the laser which is sensitive to the laboratory environment (humidity and temperature). Outside of this zone, the microstructure was not changed, and the crack path was strongly influenced by it, as shown in Fig. 7 (c). The cracks propagated both integranularly (preferably along phase boundaries ferrite/pearlite) and transgranularly (both in ferrite and pearlite grains) No shear-controlled Stage I crack propagation was observed. Hence physically small cracks were initiated from the starter notches.



(a) artificial notch and heat damage area

(b) crack propagation behavior affected by microstructure

Figure 7. SEM observation of artificial notch and crack growth on etched surface.

The notch shape in the depth direction was observed on the fracture surface by SEM in the case of the single notch, as shown in Fig. 8. The artificial notch had a very complicated front profile. The asperity size seems to be correspondent to a grain size, which indicated that ablation by the fs-laser at boundaries is stronger than inside grains. Fig. 8 shows that the microcrack initiated from the notch root also extended in depth direction.

Thus the fs-laser micromachining can produce small structure with a well-defined shape at a specific area in metallic materials. Although a small heat affected zone was formed around the notch, it didn't influence crack propagation after the crack tip left the damaged area. Since the heat affected zone can be minimized less than 1 μm (Luft et al., 1996), this problem can be solved by optimizing parameters depending on material properties such as heat conductivity or grain size.

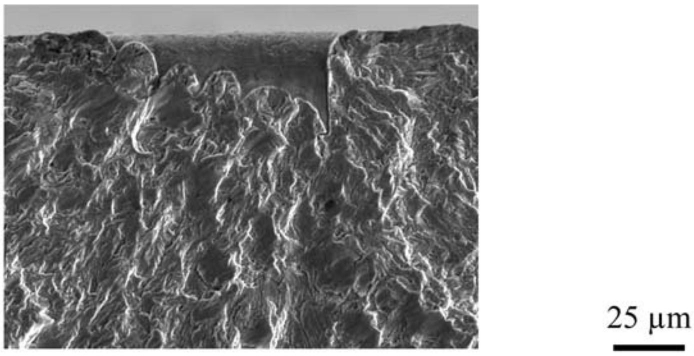


Figure 8. Fracture surface around artificial notch.

3. Conclusions

In this study some artificial small notches were machined in steels by the fs-laser technique. They worked as a starter notch and growth of physically small surface cracks can be studied in a systematic way. The fs-laser technique allows to place a starter crack of pre-defined shape at a specific location. This is very useful especially in inhomogeneous or anisotropic materials. It is still necessary to optimize laser parameters depending on target materials, but the fs-laser machining technique is a promising candidate for introducing crack-like notches in metallic materials.

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