# JAERI femtosecond pulsed and Tens-kilowatts Average-powered Free-electron Lasers and their Applications of Large-Scaled Non-thermal Manufacturing in Nuclear Energy Industry

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## 1. Introduction

We first reported the novel method that femto-second (fs) lasers of the low average power Ti: Sapphire one, the JAERI high average power free-electron laser, excimer laser, fiber laser and so on [1,2] could peel off and remove both stress corrosion cracking (SCC) origins of the cold-worked (CW) and very crack-susceptible material, and residual tensile stress in the hardened surface of low-carbon stainless steel cubic samples for nuclear reactor internals as a proof of principle experiment except for the last and third origin of corrosive environment. Because it has been successfully demonstrated that the fs lasers could clearly remove the two SCC origins, we could resultantly prevent the cold-worked SCC in many field near future.

The SCC is a well known phenomenon [3, 4, 5, 6] in modern material sciences, technologies, and industries, and defined as an insidious failure mechanism that is caused by the corrosive environment, and the crack-susceptible material and the surface residual tensile stress simultaneously. There are a large number of famous SCC examples for damaging stainless steels, aluminum alloys, brass and other alloy metals in many different cases. In many boiling light-water reactor (BWR) nuclear power plants and a few pressurized light water reactor (PWR) ones in Japan and the world [3, 4, 5, 6, 7] up to now, a large number of the deep and wide cracks have been recently found in the reactor-grade low-carbon stainless steel components of core shroud, control-blade handle, re-circulating pipes, sheath and other internals in the reactor vessel under very low or no applied stresses. These cracks have been thought to be initiated from the crack-susceptible like very small-sized cracks, pinholes, concentrated dislocation defects and so on in the hardened surface, which were originated from cold-work machining processes in reactor manufacturing factories, and to be insidiously penetrated widely into the deep inside under the residual tensile stress and corrosive environment, and under no applied stress during a much shorter term operation. Most people had thought to be unavoidable that Japanese economy would be damaged more or less because most of the nuclear power plants near Tokyo were shut-down during the last summer because of the CWSCC failures. As it was fortunately a cold summer last year because of global climate disorder, Japan and the Japanese domestic electric power companies could have a narrow escape from a large scale black-out in many prefectures near Tokyo and Tokyo metropolitan area.

## 2. Sample preperations

The low-carbon type 316, 304 and other austenitic stainless steel materials commonly used in nuclear reactor internals were prepared and cold-worked to introduce high residual tensile stress, crack-susceptibility and hardening in the one side using a conventional multi-purpose milling machine before the cutting, characterizing the cold-worked surface hardness, suceptibility and tensile stress, and fs laser peeling-off. As a lot of the reactor core shrouds and others have been found to be damaged by CWSCC during their operation and to be manufactured and cold-worked to finish by a disk-sander and a bite of a huge turning mill in the factories, the same stainless steel material with them and the multi-purpose milling machine were used to simulate or to reproduce their cold-work processes like breaking-down surface grains and lattice microstructures.

## 3. fs laser peeling off

After the stainless steel material sheet was cut into about one centimeter cubic samples of several tens, typical depth of the hardened surface zone was measured to be about several tens to a hundred micrometer. Each cube of them was used as a standard test sample being prepared in the same manner to compare with each other in different peeling-off and testing conditions. The laser typically irradiated to peel off about 2mm by 2mm square area in the depth of 0.05-0.75mm without any heat effects around the central part of the cold-worked, hardened and tensioned one in air atmosphere. Each of the irradiated samples was cut into 2 pieces by a sharp and thin ceramic disc to have a rectangular 2mm by 1mm peeled-off strip area under water-spraying and cooling. One of the half pieces was used to measure hardness distribution along the depth, and another of them used to measure the residual stress strength and direction of compressing or tensioning in the peeled-off strip and hardened side.

The half piece sample for the hardness testing was polished carefully to peel off the damaged surface layer spraying water and diamond powder. Then, the cross-sectional surface of the half was electrochemically etched to get rid off the damaged layer by 10% oxalic acid solution. The etched surface was used to measure hardness distribution along the depth from the cold-worked surface to the deep inside by a Vickers type micro hardness testing machine [8]. Results of the hardness distribution measurements have shown that the fs laser completely peeled off the susceptible and the hardened zone.

### 4. Residual tensile stress

A commercially-available small area X-ray diffractometer[9] was used to analyze residual stress in the peeled-off strip, and to confirm no effective residual stress in it. As typically measured in the diffractometry, the residual tensile stress which was introduced to range from 500 to 600 MPa by the cold-work were removed from the fs laser peeled-off strip.

### 5. Hardness testings

The typical value shows that the hardness one near the surface was measured to be very high, around 470 kg/mm$^2$, and the artificially-introduced residual stress by the milling and other cold workings measured to be tensioned along the surface. In contrast with the high hardness values, the measured hardness ones around the fs laser peeled-off area of about 2mm by 2mm square were as low as the original low-carbon stainless steel austenitic material deep inside, and the fs laser peeling-off could remove the cold-worked and hardened one and make no additional hardened zone on the strip surface. .

### 6. Results and Conclusion

The novel method of the fs laser-peeling off two SCC origins of the susceptible zone and residual tensile stressed ones without additional heat effects in the stainless steel except for the corrosive and environmental was firstly demonstrated utilizing a half watt or less Ti-Sapphire fs laser [1] as the proof-of principle experiment to evaluate a feasibility utilizing tens kW class fs free-electron laser (FEL) peeling and finishing. A $MgCl_2$ SCC test [10] for the samples has shown to be no crack of the CWSCC and a few tens of other shallow cracks in the peeled-off strip, and clearly indicates successful removal of the two origins. Figure shows a typical SCCs of $10^5$ /cm$^2$ after the test.

All of the commercially-available fs ultra-fast lasers of Ti-Sapphire laser, excimer laser, fiber laser and so on[7] except for high power fs FELs have intrinsically no capability and no future possibility to produce a fs and kW high average power [1]. It is thought that the high average power and fs FEL[2] has only and enough capability to peel off the two SCC origins and to prevent their damages of the nuclear reactor pressure vessel internals like the core shroud, pipes, and other structural components for realizing at least several times longer interval than current life expectation spans of the nuclear reactor safely, easily and quickly in low cost near future. There is a large possibility that we could apply the novel fs laser removal method with a large number of the similar boiling and steam generating plants or devices which were made of stainless steel and other iron alloys, and other metal alloys like Aluminum one, Brass and other ones to prevent their CWSCC damages near future if the same or the similar origins will govern their CWSCC failure processes.

Figure, It shows a typical CWSCCs of $10^5$ /cm$^2$ after the test on the cold-worked low carbon stainless-steel sample.

### References

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