NIPPON STEEL TECHNICAL REPORT No. 101 NOVEMBER 2012

Technical Review

UDC 539 . 388 . 1

Approaches for Fundamental Principles 2: Total Solution for Fatigue of Steel

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1. Introduction

Many steel structures are fabricated by welding steel materials together. When a fracture occurs in a welded steel structure, the origin is often a weld zone. The reason for this is that the weld zone is structurally susceptible to stress concentration and that there is the possibility of various defects. From the standpoint of cutting the lifecycle cost of steel structures, reducing the environmental impact, ensuring the safety of steel structures, and so on, there is growing social expectation for structures to have a longer life and be lighter in weight. Accordingly, the application of high-performance steel materials in structures is being increasingly sought. As a consequence, with the expansion in the use of high-performance steel materials, the weld zones are required to be more reliable.

It is said that 80 percent of fractures in steel structures are ascribable to phenomena relating to steel fatigue. With the aim of coping with steel fatigue, various efforts have been made, such as implementing structural design that prevents stress concentration, reducing welding defects (for welded structures) and applying surface grinding and other after-treatments, as well as employing high-quality steel materials. However, none of them can be said to be wholly satisfactory.

Nippon Steel Corporation has long engaged in the development of technology to improve the reliability of weld zones in steel structures. Among others, the company has been striving to establish and offer a total solution for fatigue fractures hoping to deliver high-performance steel products which are safe and secure. The total solution for steel fatigue that the company seeks consists mainly of: (1) steel materials that have excellent resistance to the occurrence/propagation of fatigue cracks, (2) highly efficient welding materials or after-treatment technology to restrain the occurrence of fatigue cracks, and (3) technology to accurately estimate fatigue life. In this technical review, we describe the above total solution for steel fatigue.

2. Steels Having High Fatigue Characteristics

It is generally known that the fatigue limit, σ_w, of a smooth-surfaced steel material free from stress concentration is almost proportional to its tensile strength, TS, and that the value of σ_w is about 0.4 - 0.6 TS for steel materials whose TS is within about 1,300 MPa. It is also known that the rate of fatigue crack propagation (i.e. the distance of propagation per cycle of stress amplitude) in steel materials does not normally depend on the steel structure and is almost the same in the ferrite, bainite and martensite phases, as long as the effective stress intensity factor range, ΔK_{eff}, a fracture mechanics parameter that represents the driving force for fatigue crack propagation, is the same. On the other hand, on the basis of many years of research into steel fatigue, the company has developed multiphase steels that show a high fatigue characteristic not found in conventional steel materials. Below, we introduce the Fatigue Moderation (FM) steel as an example of steel plate and the Cu-added, ultralow-carbon steel as an example of steel sheet.

The FM steel has a unique structure consisting of alternate layers of ferrite and martensite phases (see **Fig. 1**)[1-4]. When a fatigue crack propagates through the laminar structure perpendicularly to the layers, the propagation is markedly delayed. At $\Delta K = 20$ MPam$^{1/2}$, the rate of fatigue crack propagation in the FM steel is about one-tenth that in conventional steel. Thus, the FM steel shows excellent fatigue resistance. In conventional steel, a fatigue crack propagates linearly irrespective of the steel structure. In the FM steel, it can be seen that a fatigue crack propagates by arresting, deflecting, and branching out right above each martensite phase (see **Fig. 2**). The mechanisms by which the fatigue crack arrests, deflects and branches out are considered as shown in **Fig. 3**. Firstly, owing to the presence of a hard, flat martensite phase, the cyclic plastic deformation of the front end of the crack is restrained, whereby the resistance to crack propagation increases. Secondly, the expansive stress (the residual compressive stress in the martensite phase) that occurs during martensite transformation causes the driving force for crack propagation

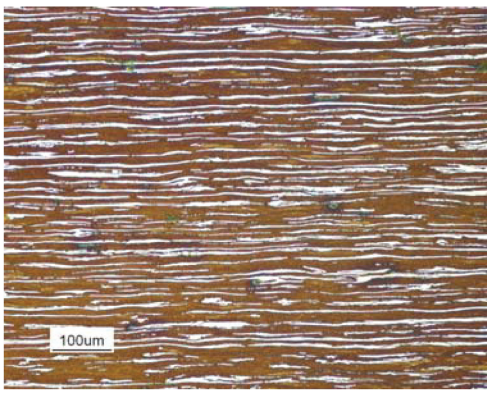

Fig. 1 Microstructure of FM steel (RD) (white: martensite phase, brawn: ferrite phase)

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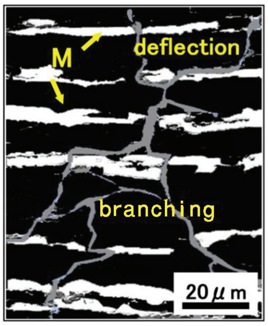

Fig. 2 Crack propagation behavior in FM steel (crack propagation direction: top to down)

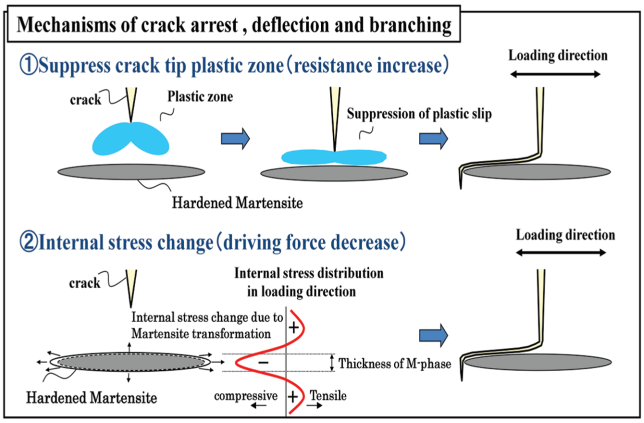

Fig. 3 Mechanisms of crack arrest, deflection and branching in FM steel

to decrease. Those mechanisms have been discussed quantitatively with the aid of crystalline FEM analysis[5, 6] and the mean field theory of Mori-Tanaka.

The representative composition of 490-MPa-class FM steel is 0.12C-1.2Mn-0.5Si and its mechanical properties are as follows: yield stress [YS] = 394 MPa; tensile strength [TS] = 506 MPa; elongation [EL] = 22%; thickness-wise reduction [Φz] = 75%; and Charpy absorbed energy (−40℃) [vE_{-40}] = 239 J (cross section in rolling direction), 142 J (transverse section). Since the FM steel is excellent not only in fatigue characteristics, but also in strength and toughness balance, it is expected to become popular in the fields of shipbuilding and bridge construction in the future.

The Cu-added, ultralow-carbon steel is a ferritic steel in which the presence of Cu is controlled.[7-9]

Solution-strengthened Cu steel (typical composition 0.002C-0.2Mn-0.01Si-1.5Cu, tensile strength [TS] = 350 MPa), which is an ultralow carbon steel with 1.5% Cu added, hot-rolled, air-cooled and heat-treated at 450℃ for one hour, is characteristic in that the fatigue limit [σ_w] is 0.69 TS, greater than the 0.4 - 0.6 TS of conventional steels (see **Fig. 4**). The Cu-added steel is also characteristic in that it does not show repetitive softening in low cycle fatigue tests.

It has been confirmed that after a fatigue test, the substructure of the steel with solute Cu has a veined structure, whereas that of the reference steel without Cu appears cellular (see **Fig. 5**). It is considered that the solute Cu prevented the shift in position of dislocations, restrained the formation of a cellular structure, and narrowed the gap between slip bands on the surface, thereby improving the steel fatigue strength.

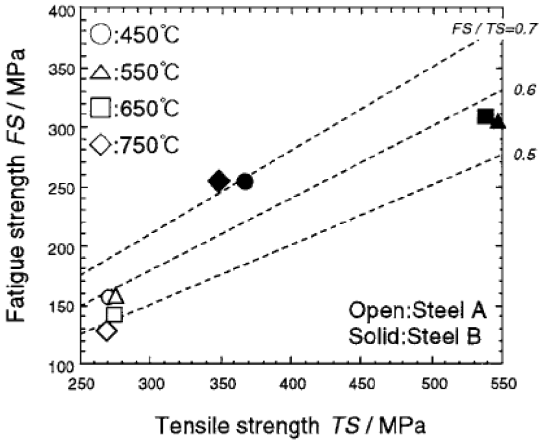

Fig. 4 Relationship between tensile strength and fatigue strength (Steel A: without Cu, Steel B: Cu 1.5%)

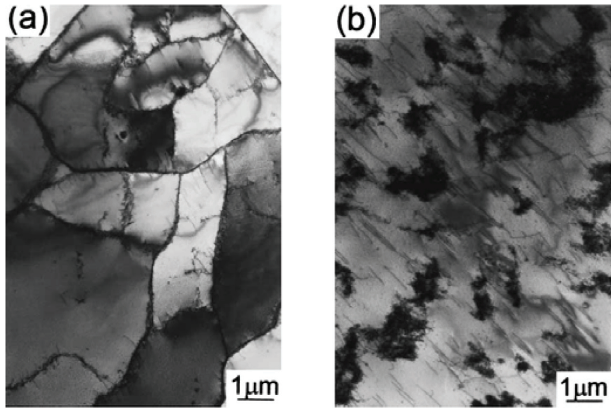

Fig. 5 TEM observation after cyclic loading (1,000 cycle) ((a): steel without Cu, (b): steel with Cu 1.5% solid soluted)

The Cu-added, ultralow-carbon steel permits changing the presence of the Cu from solid-solution state to precipitation state by controlling the heat treatment temperature. It also permits controlling the strength between 300 MPa and 550 MPa. Thus, the steel is expected to find more applications in the field of automobiles.

3. Measures against Weld Zone Fatigue

As a measure against the fatigue of weld zones, restraining the occurrence of fatigue cracks would be ideal. To that end, it is important to prevent local cyclic plastic deformation on a microstructural level. This is because local cyclic plastic deformation is known to induce the formation of a persistent slip band and cause a crack along the slip surface. In order to restrain cyclic plastic deformation, it is necessary not only to increase the strength of that part of the steel susceptible to cracking, but also to decrease the stress acting upon each crystal grain of the steel to such a level that plastic deformation does not occur. Basically, it is indispensable to decrease the mean stress and restrain the stress concentration.

In order to improve the fatigue strength of weld zones, various methods have been developed and put to practical use. Nippon Steel has long been tackling the development of techniques to improve the fatigue characteristics of steel materials. In particular, as the technology to reduce mean stress and restrain stress concentrations at weld toes which are often the origins of fatigue cracks in welded steel structures, the company has been focusing on Ultrasonic Impact Treatment (UIT), which permits improving the fatigue strength significantly by simple treatment after welding, and the Low Transformation Temperature (LTT) welding consumable that helps improve the fatigue strength of as-welded steel.

The UIT technology*[1)] is a kind of peening technology utilizing ultrasonic vibrations. By pressing a steel pin excited ultrasonically against the weld toe, etc., the occurrence of a fatigue crack from the treated region is restrained.[10-13)] The fatigue life of a cruciform joint (KE36 steel) whose weld toe was subjected to a UIT treatment (pin diameter 3 mm, frequency 27 kHz, output 1,000 W) was several to about ten times longer than an identical joint without UIT treatment. Thus, UIT improves the fatigue properties of welds markedly (see **Fig. 6**). This effect of UIT has been confirmed by a large-scale test of full-sized welded joints. In addition, the application of UIT to steel with high fatigue strength mentioned above has proved to produce a noticeable multiplication effect.[14)]

It is estimated that the mechanism by which UIT restrains the occurrence of fatigue cracking is the combination of these effects: (1) A plastic flow which is generated when the pin is pressed against the weld toe introduces a residual compressive stress into the part being treated, thereby causing the cyclic mean stress to decrease, (2) The plastic flow causes the shape of the pin with a curved tip to be transcribed to the weld toe, thereby expanding the curvature of the weld toe and reducing the stress concentration in the neighborhood of the weld toe, and (3) The crystal grains at the surface of the part being treated increase in hardness as they are refined (see **Fig. 7**).

On the basis of the above mechanism, Nippon Steel has proposed standards for work management, specifying, for example, continuation of the treatment till the weld toe disappears. Those proposals have been accepted in various fields.

As an example of practical application, UIT has been widely used to improve the fatigue strength of various types of steelmaking equipment, thereby helping to prolong the equipment life. In the field of shipbuilding, UIT has been approved by the LR, NK and ABS and has begun to be applied at large shipbuilding companies. For example, UIT was adopted for the "Brazil Maru," a 320,000-ton ore carrier, to ensure a fatigue life exceeding 25 years (see **Fig. 8**). In addition, the UIT research committee (members: a university, NK, five shipbuilding companies, and Nippon Steel) organized for the domestic shipbuilding industry is studying new common structural rules for the International Association of Classification Societies (revision of IACS-CSR). In the field of bridge construction, UIT has been registered in the New Technology Information System (NETIS) of the Ministry of Land, Infrastructure, Transport and Tourism, and its application, mainly in the repair of existing bridges, is being discussed in earnest. For ocean structures, UIT was adopted to improve the fatigue strength of the jacket of the Haneda Airport D Runway (see **Fig. 9**). There, UIT is applied to the weld toes extending over 40 km to improve reliability against the repetitive loads acting upon them during landings and takeoffs. In the future, UIT is expected to be used more widely in this particular field too.

The LTT welding consumable is one with an austenite phase-stabilizing element added to lower the martensite transformation temperature, Ms.[15, 16)]

Generally speaking, when an ordinary welding consumable is used, the weld metal that is locally heated and melted during welding, cools and shrinks at the end of welding, thereby producing a large field of residual tensile stress in the weld metal and weld toe

*[1)] UIT (Ultrasonic Impact Treatment) is a registered trademark of Applied Ultrasonics, L.L.C.

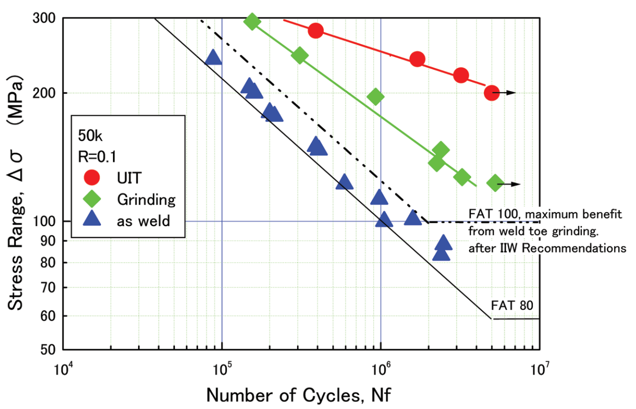

Fig. 6 Fatigue test results of cruciform joint (▲: as welded, ◆: with grinder, ●: with UIT)

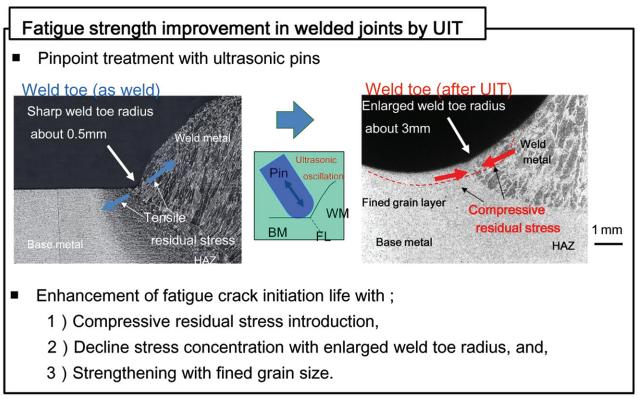

Fig. 7 Enhancement mechanisms of fatigue crack initiation life by UIT

Fig. 8 UIT treatment in ore-carrier; "Brazil Maru" (Photo by Mitsui Engineering & Shipbulding Co., LTD)

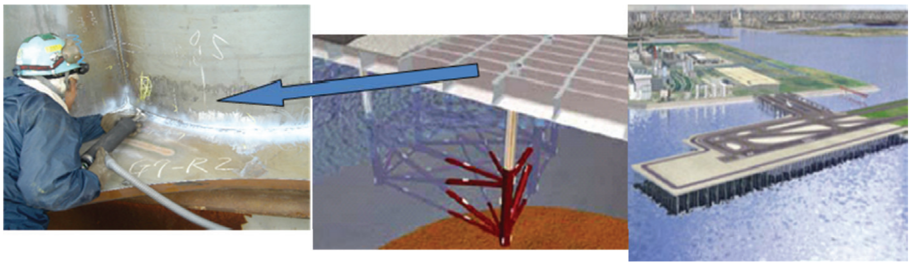

Fig. 9 UIT adopted in expansion project of “D” runway in Haneda airport (Illustration by Tokyo International Airport Runway D Exterior Construction JV)

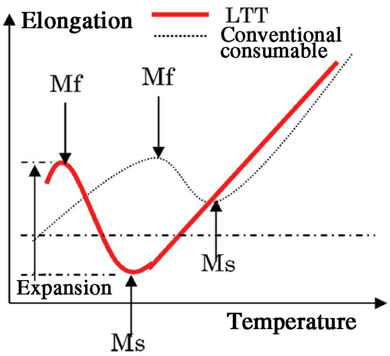

Fig.10 Thermal expansion behavior of LTT welding consumable (Ms = 350°C)

under constraint from the surrounding members. It has been known that the above residual tensile stress increases the mean stress of the cyclical load applied to the members, causing the steel fatigue characteristic to deteriorate markedly. The LTT welding consumable was developed to solve this problem. It has Ni, C or some other element added which stabilizes the austenite phase to lower the Ms point to about 350℃, lower than around 550℃ at which the plastic constraint occurs, so as to cause a field of residual compressive stress to be introduced to the weld metal and toe region at room temperature by the expansion in volume due to martensite transformation (see **Fig. 10**).

When an LTT welding consumable (0.4C-2Mn-0.8Si-1Cr) with 2.5% Ni added was applied to a 780-MPa-class lap joint, a large residual compressive stress of about -450 MPa was measured in the neighborhood of the weld toe. It has been confirmed using a two million-cycle bending fatigue test that the LTT welding consumable offers fatigue strength of about 340 MPa as compared with 220 MPa with a conventional welding consumable. The behavior of the generation of residual compressive stress has also been confirmed by FEM analysis.[17]

In the future, it is expected that LTT welding consumable will become much more popular in the fields of automobiles, construction equipment and bridges.

4. Estimation of Fatigue Life

In designing and maintaining any structure, it is extremely important to know the life of each of the structural members that are subject to a fatigue fracture under cyclical stress. Nippon Steel has long accumulated fatigue test data for various types of steel materials and organized them into databases. The company has also been striving to develop technology to estimate the life of steel materials, including a numerical analysis of steel life. On the basis of huge volumes of systematized test data, it has proposed a number of life estimation techniques. As a simple technique, for example, there is the Locally-Expanded Modified Goodman Diagram (LEMGD) that takes into account the steel strength, local stress concentration, and local residual stress, and that permits estimating the fatigue life from calculated fatigue strength.[13] Another example is a technique that has expanded the life estimation by integration of the Paris law into the ultralow-cycle region.[18] Recently, the company has succeeded in establishing a welded structure fatigue life prediction system that takes into account the arrangement of steel members, stress concentration, residual stress, and even random loads in the actual structure, and that offers sufficient accuracy for practical application.

Fig. 11 presents an outline of the fatigue life prediction system for welded structures.[19] With this system, it is possible to estimate

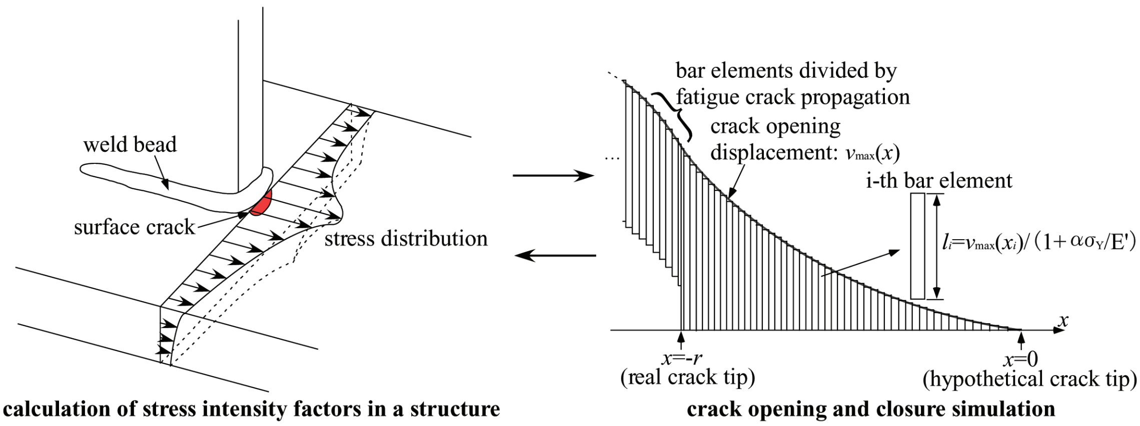

Fig.11 Outline of the fatigue life estimation system

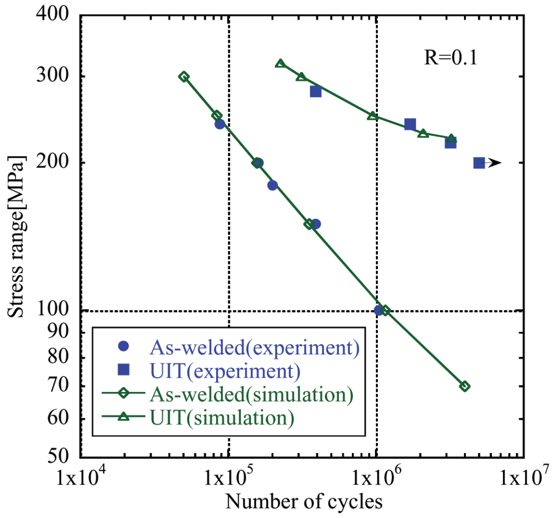

Fig.12 Comparison between test results and estimated results in S -N diagram of cruciform joint

the fatigue life of a welded structure by analyzing the propagation behavior of a microscopic initial crack assumed to have occurred in the weld toe with the aid of analysis of the surface crack stress intensity factor using the weight function method and a simulation of crack opening/closing using a crack binding force model.[20] Next, the stress intensity factor can be calculated taking into consideration the influence of stress concentrations due to the shape of the weld and the influence of complicated residual stress distribution due to welding and peening. Then, by estimating the crack opening/closing load or Re-tensile Plastic zone Generated (RPG) load using an analysis of the behavior of plastic deformation of the crack front and the crack surface contact,[21] it is possible to accurately predict the fatigue life of the welded structure, including the influence of the loading sequence and stress ratio.

As an example of application of the system, **Fig. 12** shows the results of an analysis of S-N diagrams of cruciform joints with and without UIT treatment.[22] In the present analysis, the stress distribution in each test piece was calculated by an elastic analysis with an FEM model using solid elements, and the welding residual stress distribution in each test piece was calculated by a welding simulation using thermal elastic-plastic FEM with a similar model. As the residual stress distributions in the UIT-treated parts, the results of measurement obtained by the neutron diffraction method were used.[23] In the analysis of fatigue crack propagation, a microscopic semicircular crack, 0.15 mm in depth, was set initially and the modified Paris-Elber law was applied to the fatigue crack propagation to estimate the fatigue life by which the crack would propagate in the test piece. The analysis results agree very well with the experimental results, proving that the system permits quantitative estimation of the fatigue characteristics of welded joints, including the effects of UIT and other after-treatment techniques.

In order to estimate fatigue life with a high degree of accuracy, it is necessary to input an accurate residual stress distribution to the system. In this respect, Nippon Steel has established an elastic-plastic thermal stress analysis,[12] and a nondestructive method of measuring three-dimensional residual stress distributions, which use neutron diffraction.[23,24] With this method, it is possible to evaluate complicated residual stress distributions in welded structural members.

5. Conclusion

So far, we have discussed our total solution for the fatigue of steel materials. It is considered that the improvement in the fatigue characteristics of welds due to the total solution will improve the reliability of steel structures, thereby contributing much to prolonging the life of social infrastructure, reducing environmental impact, and enhancing safety and security in our society. In the future, we would like to continue tackling the development of ever more reliable solutions to fatigue of steel materials so as to deliver safer, more secure steel products to our customers.

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