

レーザピーニングによる高張力鋼リブ溶接部の疲労強度向上効果の検証

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1. 緒言

近年、構造物の大型化に伴い鋼構造物の軽量化が求められ、それを可能とする引張強さが 570MPa 以上の高張力鋼が、水圧鉄管や長大橋等の溶接構造物に使用されている。高張力鋼は構造用普通鋼と比較して、板厚の低減による構造物の軽量化が可能だけでなく、溶接作業にとっても溶接工数の短縮、材料の節約などの点で有利となる¹⁾。このため、構造物の大型化に対して、高張力鋼は大きな役割を果たすと考えられる。しかし、構造物の溶接部では、止端部等の応力集中が主な原因となって疲労き裂が生じる。この応力集中は形状に大きく依存し、母材の強度には依存しないことが知られている。このため、疲労強度の観点からみると、高張力鋼は普通鋼に比べ強度が高いものの、高張力鋼を部材とした溶接構造物の疲労強度は、普通鋼を部材とした溶接構造物とほとんど変わらない。よって、溶接部の疲労強度が高張力鋼を使用するメリットを大きく損なわせている。

研究代表者らは、数ある溶接部の疲労強度改善方法の中からレーザピーニングに注目した。レーザピーニングは、水等の透明媒質中に設置された材料に数 ns～数十 ns のパルス幅のレーザを照射して高圧のプラズマを発生させ、その衝撃力を利用して材料表面の強度上昇を図る技術である²⁾。照射時の写真を Fig.1 に示す。レーザピーニングを行うと、材料の表面に高い圧縮残留応力が生成されるため、応力腐食割れの防止に有効であることが知られている³⁾。実際に、沸騰水型原子炉の炉心シュラウドや加圧水型原子炉の原子炉容器下鏡を貫通する中性子計測系用の管台内面等に、応力腐食割れ予防保全対策として用いられている。レーザピーニングではパルス毎の照射条件を厳密に制御することが可能なため、より信頼性の高い処理を行うことができる。また、本装置は照射位置がコンピュータ制御により厳密に制御できるため施工のやり残しがなく、小さな照射径で連続的に動かしていくので複雑な対象物や局所への適応性も高い³⁾。さらに、一部で用いられているショットピーニングなどの他のピーニング技術と比較して、その効果がより深くまで及ぶとの報告もある⁴⁾。圧縮残留応力の生成による疲労強度の向上効果についても、オーステナイト系ステンレス鋼⁵⁾、アルミニウム合金^{6),7)}、チタン合金⁸⁾等に対する疲労試験が行われている。しかし、レーザピーニングは新しい技術であるため、現在橋梁や建築物等の大型構造物に最も多く用いられている構造用鋼材や、ましてやその溶接部に対する適用性についての研究はなされていなかった。

そこで、疲労き裂が大きな社会問題となっている橋梁等の大型構造物溶接部に、レーザピーニングを適用するための基礎的な研究として、構造用普通鋼材に対するレーザピーニングの施工条件を明らかにした^{9),10)}。さらに、レーザピーニングによって

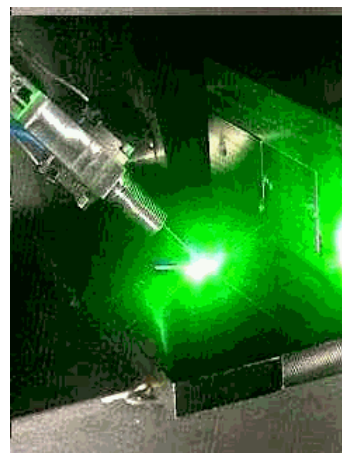


Fig. 1 Underwater laser peening

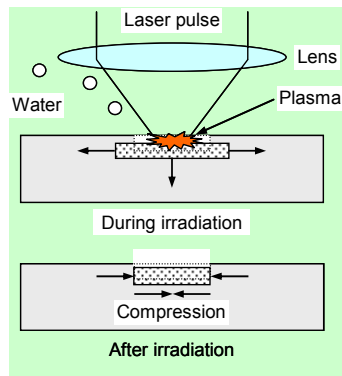


Fig.2 Mechanism of residual stress improvement by laser irradiation

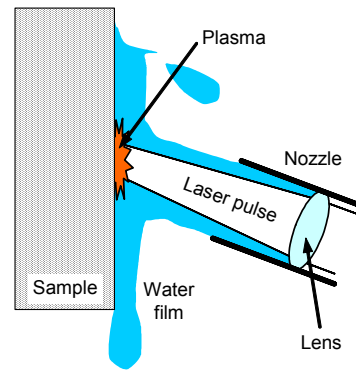


Fig.3 Laser peening process with water flow from nozzle

普通鋼材 (SM490) の溶接部に圧縮の残留応力が生成され、普通鋼材溶接部の疲労寿命が大きく延びることが確かめられた^{10)~12)}。しかしながら、より強度の高い高張力鋼溶接部に対して、普通鋼材 (SM490) へ適用した条件でレーザピーニングを施した場合の効果は明らかでない。

本研究では、高張力鋼として HT780 を対象とし、レーザピーニングにより HT780 材表面に圧縮の残留応力が生成されるか否か、また、それによって HT780 材溶接部の疲労寿命が延びるか否かを明らかにすることを目的とする。

2. レーザピーニングの基礎プロセス

レーザピーニングによる残留応力生成のメカニズムを模式的に Fig.2 に示す³⁾。アブレーション閾値を超える強いレーザパルス在水中の材料に照射すると、材料の表層がプラズマ化して表面に高圧のプラズマが発生する。水中では水の慣性がプラズマの膨張を妨げ、狭い領域にレーザのエネルギーが集中する。その結果、プラズマの圧力は空気中と比較して 10~100 倍となり数 GPa に達する¹³⁾。この圧力によって衝撃波が発生し、材料中を伝播する。衝撃波による応力によって塑性変形が生じ、周囲の未変形部からの拘束によって材料の表層に圧縮残留応力が生成される¹⁴⁾。このレーザパルスを移動させながら対象物に連続的に照射することにより、表面にばらつき無く一様に残留応力を生成させることが出来る。

今回使用したレーザは市販の小型 Nd:YAG レーザであり、パルスエネルギーが小さいため伝送路に光ファイバを使用することが可能である¹⁵⁾。また、プラズマの膨張を抑制するためには厚さ 0.1mm 程度の水膜が必要であるが、橋梁の溶接部などを対象とする場合には、Fig.3 に模式的に示すように、ノズルから水を噴きかけながらレーザを照射することによって施工することができる。このように、レーザピーニングは、工場のみならず現場でも適用できる技術であると考えられる。

3. レーザピーニングによる残留応力の変化

レーザピーニングによって、高張力鋼表面に圧縮の残留応力が生成されるか否かを明らかにするため、レーザピーニングを施した高張力鋼 (HT780) の母材とリブの回し溶接止端部の残留応力を測定した。これらをレーザピーニングを施していない試験体の残留応力と比較することによって、レーザピーニングによる残留応力の変化を明らかにした。

Table 1 Mechanical property

	Mechanical property			
	σ_y (MPa)	σ_u (MPa)	δ (%)	YR (%)
HT780-1	789	842	19	94
HT780-2	804	823	21	95
Welding wire*	710	830	24	—

* : the value of catalogue

Table 2 Chemical composition

	Chemical composition (%)											
	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	B	Ceq
	$\times 10^{-2}$		$\times 10^{-3}$		$\times 10^{-2}$				$\times 10^{-3}$			$\times 10^{-2}$
HT780-1	19	23	145	9	1	—	—	—	—	—	1	44
HT780-2	15	36	120	12	1	1	1	10	12	0	1	42
Welding wire*	8	38	125	9	11	—	222	—	63	—	—	—

Ceq=C+Si/24+Mn/6+Ni/40+Cr/5+Mo/4+V/14 * : the value of catalogue

3.1 母材における残留応力

ロットが異なる板厚 9mm の 2 つの高張力鋼 HT780 材(以下, HT780-1, HT780-2 と称す)に対して, レーザピーニングを施していない箇所と施した箇所の表面残留応力を測定した。2 つの鋼材の機械的性質と化学組成を **Table 1, 2** に示す。

レーザピーニングの照射条件は, 普通鋼(SM490)に適用した条件と同様で, パルスエネルギー:200mJ, スポット径:0.8mm, 照射密度:3,600Pulse/cm²とした⁹⁾。照射時には, 試験体を載せたステージを移動させながら 1/60mm ピッチでパルスレーザを照射し, 10mm 移動した後に折り返して 1/60mm 下のラインを照射した。これを繰り返すことによって 10mm×10mm の範囲を照射した。残留応力の測定には, X 線源に Cr-K α (17kV, 2.0mA)を使用した X 線回折法($\sin^2 \phi$ 法)を用いた。

測定結果を **Table 3** に示す。値は 2 カ所の平均値である。 σ_x がステージの移動方向の残留応力成分, σ_y がそれと直角方向の残留応力成分である。表中には, $\sin^2 \phi$ 法から求まる最確値と, 信頼区間(1 σ)を±の後に記している。信頼区間は最大で±30MPa, ほとんどが±10MPa 程度である。レーザピーニングを施していない箇所の残留応力は σ_x , σ_y 共に-6~-70MPa 程度の圧縮の残留応力が生成されている。これは, 鋼板製作時の冷却過程で生成したものと考えられる。一方, レーザピーニングを施した箇所では σ_x で-170~-190MPa, σ_y で-300~-330MPa の大きな圧縮の残留応力が生成されている。また, 残留応力成分 σ_x と σ_y を比較すると σ_y のほうが大きな圧縮の残留応力に

Table 3 Results of residual stress measurement

	① without Laser peening		② with Laser peening		Change by Laser peening (②-①)	
	σ_x	σ_y	σ_x	σ_y	σ_x	σ_y
HT780-1	-44±18	-35±30	-174±6	-312±8	-131	-278
HT780-2	-6±13	-70±7	-191±3	-330±6	-185	-260

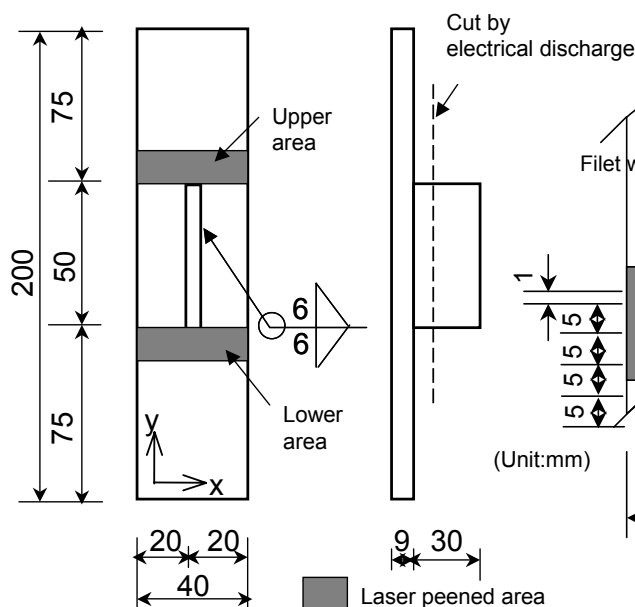


Fig.4 Specimen for residual stress measurement

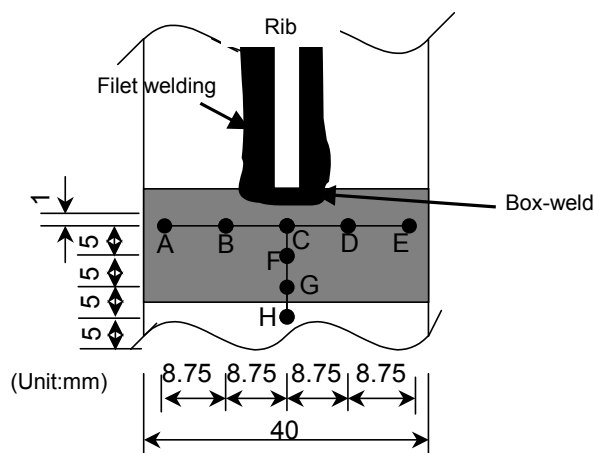


Fig.5 Measuring points of XRD

なる傾向にある。これは、レーザピーニングにおいて他の材料でも見られており、今後、その原因に関する検討が必要である。レーザピーニングを施していない箇所と施した箇所の変化量は σ_x で-150MPa 程度、 σ_y で-270MPa 程度であり、残留応力が圧縮側に大きく変化している。これらにより、高張力鋼母材でも普通鋼で用いたピーニング条件により、母材表面に大きな圧縮残留応力が生成されることが確かめられた。

3. 2 回し溶接止端部における残留応力

試験体の形状・寸法を Fig.4 に示す。試験体は、厚さ 9mm の鋼板 HT780-2 に、厚さ 6mm の鋼板をリブとして、脚長 6mm で全周すみ肉溶接を施したものを用い、リブ端部は回し溶接している。厚さ 6mm の鋼板は HT780-2 を減厚したものである。溶接法は炭酸ガスアーク溶接で、溶接材料は 780MPa 級鋼用ソリッドワイヤを用いた。ワイヤの機械的性質と化学組成のカタログ値を Table 3 に示す。ただしリブは、残留応力測定時の障害となるため、すみ肉溶接の実測の脚長である高さ 8mm の位置でワイヤーカットにより切断した。

まず、上下 2ヶ所(以下、Upper area, Lower area と称す)の回し溶接部近傍の残留応力を測定した。その後、回し溶接部にレーザピーニングを 40mm×20mm の範囲で施し、再び同じ位置の残留応力を測定した。Fig.5 に残留応力測定位置 A～H 点を示す。なお、照射条件等は母材の場合と同じであり、照射時のステージの移動方向は Fig.4 での x 方向である。測定結果を Fig.6, 7 に示す。 σ_x が x 方向(リブと直角方向)の残留応力成分、 σ_y が y 方向(リブと平行方向)の残留応力成分である。レーザピーニングを施す前(○, △印)は、試験体の端部に近い A, E 点で 100MPa 程度の圧縮残留応力が測定されたが、その他の点では 0MPa 前後であった。これに対し、レーザピーニング後(●, ▲印)は、ピーニングを施していない H 点における残留応力は変化が無かったが、ピーニングを施した点(A～G 点)では-150～-450MPa の大きな圧縮の残留応力が測定された。さらに、溶接止端部に近いほど圧縮の残留応力の変化量は大きく、特に、疲労き裂の起点となる止端部に最も近い C 点でピーニング前と後の残留応力の変化量が最も大

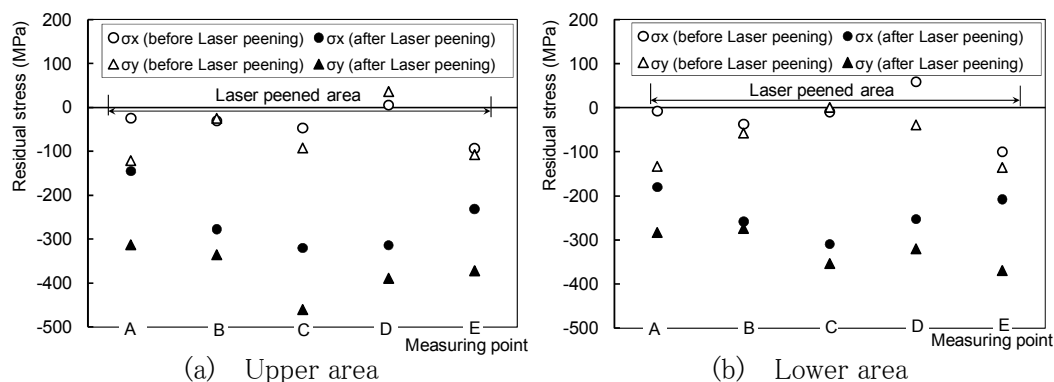


Fig.6 Results of residual stress measurement (A, B, C, D, E)

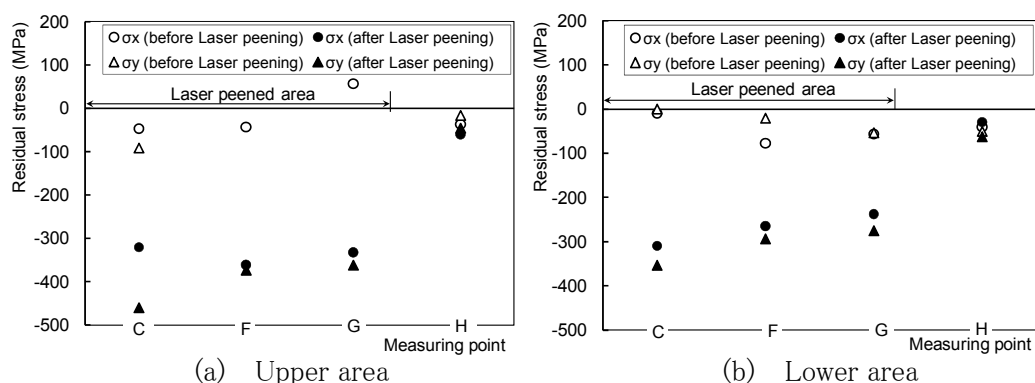


Fig.7 Results of residual stress measurement (C, F, G, H)

さい。これらより、回し溶接止端部も大きな圧縮の残留応力となっていると推定される。

4. レーザピーニングが疲労寿命に及ぼす影響

レーザピーニングにより高張力鋼の回し溶接部の疲労寿命が延びるか否かを定量的に明らかにするため、レーザピーニングを施した試験体と施していない試験体を用いて疲労試験を行った。

4.1 実験概要

300kN 一軸疲労試験機を用い、レーザピーニングを施していない試験体(以下、NP と称す)とレーザピーニングを施した試験体(以下、LP と称す)に対して、一定の応力範囲で疲労試験を行った。試験体の形状・寸法を Fig.8 に示す。試験体は、130mm の平行部を有する厚さ9mm の平板試験片に、厚さ6mm の鋼板をリブとして全周すみ肉溶接したものである。鋼材、溶接条件および溶接材料は 3.2 節と同様である。また、レーザピーニングの照射条件、位置および範囲も 3.2 節と同様である。試験体形状

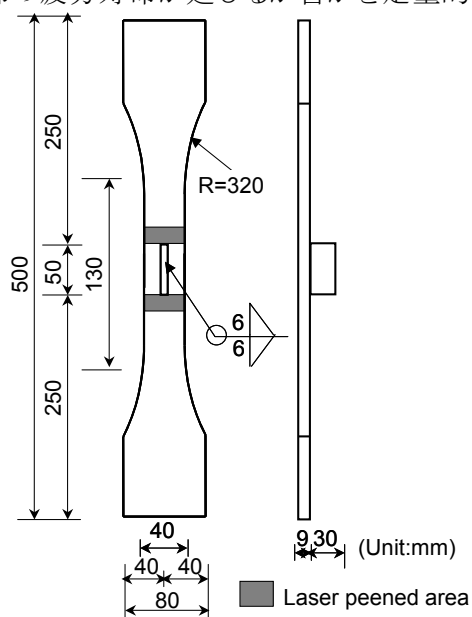


Fig.8 Fatigue test specimen



Fig.9 Photo of box-welded rib specimen and its laser peening area

およびレーザピーニング位置を Fig.9 に示す。载荷する応力範囲は, NP では 200MPa が 3 体, 250MPa が 3 体, 300・350・400・450・500・550・600MPa がそれぞれ 2 体ずつの計 20 体, LP では 300・350・400・450・500・600MPa がそれぞれ 2 体ずつ, 550MPa が 1 体の計 13 体である。応力比は 0, 試験の打ち切り限界は 10^7 回とした。

4. 2 実験結果

実験で得られた S-N 線図を Fig.10 に示す。なお, 図中の矢印は, 疲労寿命が試験の打ち切り限界 10^7 回に達したことを表している。以下, き裂発生位置, 疲労限, 疲労寿命に分けて実験結果を述べる。

4.2.1 疲労き裂発生位置

破断面の写真を Fig.11 に示す。図中の●印はき裂発生位置, 矢印はき裂進展方向を示している。NP はすべて応力集中部のある回し溶接の止端部からき裂が発生した。LP も 450MPa 以上では応力集中部である止端部からき裂が発生した。しかし, 応力範囲 350 ~ 400MPa では, レーザピーニングを施した止端部からき裂は発生せず, レーザピーニングを施していないが応力集中部のない裏面(回し溶接止端部の裏側)からき裂が発生

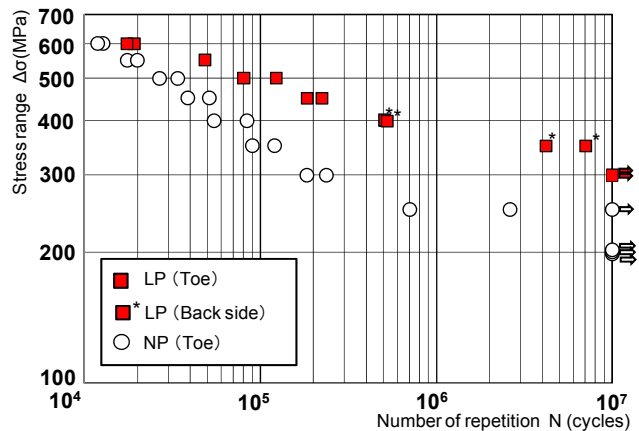


Fig.10 S - N diagram

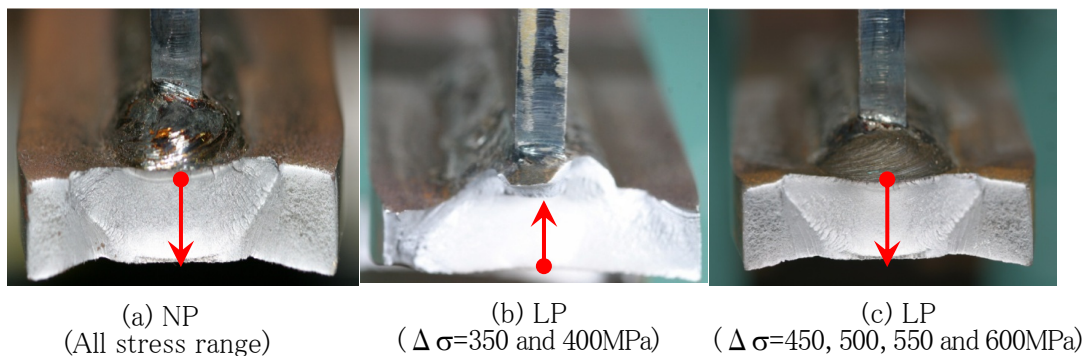


Fig.11 Fracture surface

した。

この様に、レーザピーニングを回し溶接止端部に施すと、応力範囲の大小によってき裂発生位置が変化し、比較的小さな応力範囲では応力集中のない裏面からき裂が発生することが、実験により明らかになった。

4.2.2 疲労限

NP の場合、応力範囲 200MPa で 3 体、250MPa で 3 体中 1 体が 10^7 回の打ち切り限界に達し、残り 2 体が約 7×10^5 回と 26×10^5 回で破断している。このことから、レーザピーニングを施していない試験体の疲労限は 200MPa であると考えられる。

これに対し、LP の場合は、応力範囲 300MPa で 2 体とも 10^7 回の打ち切り限界に達し、350MPa では 2 体が約 42×10^5 回と 7×10^6 回で破断している。よって、レーザピーニングを施した試験体の疲労限は 300MPa であると考えられる。さらに、応力範囲 350MPa と 400MPa では止端部ではなく裏面からき裂が発生していることから、レーザピーニングを施した止端部の疲労限は、350MPa 以上である可能性がある。

これらより、高張力鋼回し溶接止端部の疲労限は、レーザピーニングを施すことによって、応力範囲 200MPa から少なくとも 300MPa に、1.5 倍以上に上昇することが明らかとなった。

4.2.3 疲労寿命

各応力範囲での NP と LP の疲労寿命を比べたものを Fig.12 に示す。縦軸には、各応力範囲における NP 2 体の疲労寿命の平均 NP_{AVE} を 1 とした場合、LP 1 体ごとの疲労寿命がその何倍であるかを示している。図中の矢印は、疲労寿命が 10^7 回を超えたため、測定値以上であることを表している。疲労寿命は、応力範囲が 600MPa と非常に高い場合に約 1～1.5 倍であり、レーザピーニングの効果が低かった。しかし、550MPa や 500MPa の場合、疲労寿命は約 2.5 倍以上に向上した。さらに、応力範囲が小さくなるに従って疲労寿命向上効果は上昇する傾向にあり、応力範囲 300MPa では少なくとも約 50 倍以上もの疲労寿命であることがわかる。

この様に、高張力鋼の回し溶接止端部にレーザピーニングを施すことにより、応力範囲 600MPa では疲労寿命向上効果が低いものの、応力範囲 300～550MPa では疲労寿命は約 2.5～50 倍以上になり、回し溶接止端部の疲労寿命が著しく延びることが確かめられた。さらに、レーザピーニングによる疲労寿命の向上効果は応力範囲が小さいほど大きいことが明らかとなった。

5. 結言

- (1) 普通鋼(SM490)で用いたピーニング条件により、高張力鋼(HT780)母材表面に大きな圧縮残留応力が生成される。
- (2) 疲労き裂の起点となる高張力鋼の回し溶接止端部にもレーザピーニングにより、大

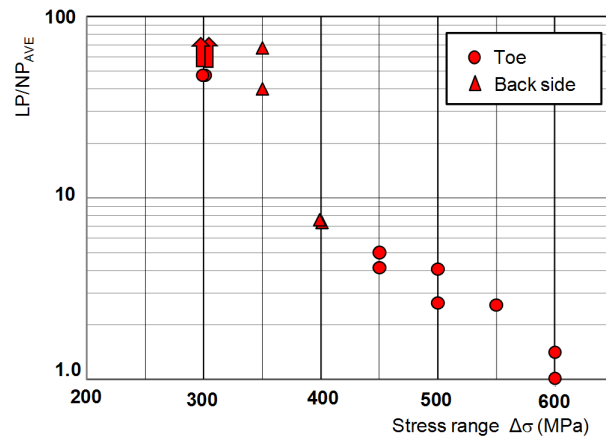


Fig.12 Comparison of between NP and LP

きな圧縮の残留応力が生成される。

- (3) レーザピーニングを施した高張力鋼回し溶接試験体では、応力範囲の大小によってき裂発生位置が変化し、比較的小さい応力範囲では応力集中のない止端部の裏面からき裂が発生する。
- (4) 高張力鋼回し溶接止端部の疲労限は、レーザピーニングを施すことによって少なくとも約 1.5 倍になる。
- (5) レーザピーニングによる高張力鋼の回し溶接部の疲労寿命の向上効果は応力範囲が小さいほど大きく、応力範囲が 300～550MPa の場合の疲労寿命はレーザピーニングを施さない場合の約 2.5～50 倍以上になる。

以上より、高張力鋼 (HT780) の回し溶接止端部に対してレーザピーニングを施すと、大きな圧縮の残留応力が生成され、それによって疲労寿命が著しく延びることが明らかとなった¹⁶⁾。

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Effect of Laser Peening on Improving Fatigue Strength of Welded Rib of High-Strength Steel

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1. Introduction

In recent times, increase in the size of steel structures has led to an increased demand for lighter steel structure; this demand has been satisfied through the use of high-strength steel with tensile strengths exceeding 570 MPa in welded structures such as penstocks and long-span bridges. Compared to mild steel, high-strength steels not only facilitate the building of lighter structures through the reduction in plate thickness, but also are easy to weld, reduce man-hours required for welding and save materials¹⁾. Therefore, high-strength steel plays a significant role in large structures. However, high stress concentration at the toe or other welded zones of the structure often results in fatigue cracking. This stress concentration is known to significantly depend on shape but not the strength of the base metal. This indicates that although tensile strength of high-strength steel is higher than that of mild steel, the fatigue strength of a welded structure employing high-strength steel does not differ greatly from that of a welded structure of mild steel. Thus, the fatigue strength at the welded part substantially reduces the advantage of using high-strength steel.

Of the various methods employed for improving the fatigue strength of a welded zone, the authors have focused on laser peening. In this process, a laser with a pulse width of several to tens of nanoseconds is used to irradiate a material placed in a transparent medium (such as water) to generate high-pressure plasma, and the strength of the material surface is improved owing to the impact force by the plasma²⁾. **Figure 1** shows underwater irradiation of laser peening. By generating large compressive residual stress on the surface of a material, laser peening is known to effectively prevent stress corrosion cracking³⁾. In fact, this method is used to prevent stress corrosion cracking in the core shroud of a boiling water reactor and the inner face of a tube stand in a neutron measurement system that runs through the lower sphere of the reactor vessel in a pressurized water reactor. Laser peening enables reliable processing as it can control the irradiation conditions for each pulse. The computerized equipment can precisely control the location and focus of the irradiating beam, and the process offers excellent adaptability to complicated and narrow zone as it involves a small irradiation diameter³⁾. It

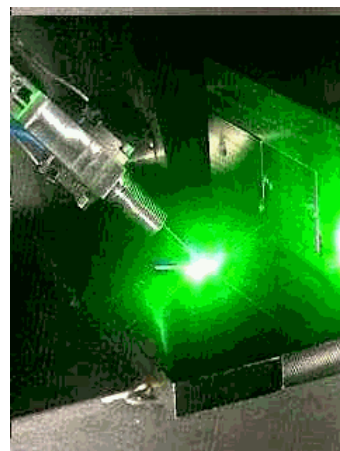


Fig. 1 Underwater laser peening

has also been reported that this laser peening method enables deeper effect compared to peening techniques such as shot peening⁴⁾. In order to improve fatigue strength through the generation of compressive residual stress, fatigue tests are often performed on austenitic stainless steel⁵⁾, aluminum alloys^{6),7)}, and titanium alloys⁸⁾. However, laser peening of neither structural steel nor its welded zones has been investigated yet; structural steel is used in large structures such as bridges and buildings.

Hence, the laser peening condition of structural steel has been clarified as a part of the basic research for the application of laser peening to the welded zones of large structures such as bridges where fatigue cracks have been a serious issue^{9),10)}. Further, it has been confirmed that laser peening generates compressive residual stress in the welded zones of structural steel (SM 490), and thus, substantially extends the fatigue life¹⁰⁾⁻¹²⁾. However, the effect of laser peening on the welded zones of high-strength steel under the same laser conditions as applied to structural steel (SM 490) is not clear.

This study targets HT780 as a high-strength steel in order to clarify whether laser peening generates compressive residual stress on the surface of HT780, and whether such stress would account for prolonged fatigue life in the welded zones of HT780.

2. Basic Process of Laser Peening

Figure 2 shows a schematic diagram of the mechanism by which laser peening generates residual stress³⁾. Irradiation by a strong laser pulse, exceeding the abrasion threshold, on a material submerged in water converts the material surface to plasma and generates high pressure plasma on the surface. Under water, the inertia of the water prevents the plasma from expanding, which consequently concentrates the laser energy in a small area. As a result, the plasma pressure becomes 10–100 times larger than in the atmosphere and reaches GPa levels¹³⁾. This pressure generates a shock wave that passes in the material. The shockwave causes plastic deformation of the material, and the restraint from the surrounding non-deformed spots generates compressive residual stress on the surface¹⁴⁾. The residual stress can be generated evenly and without scattering by continuously irradiating the object by moving the laser beam.

The laser used in this study was a commercially available small Nd:YAG, with a

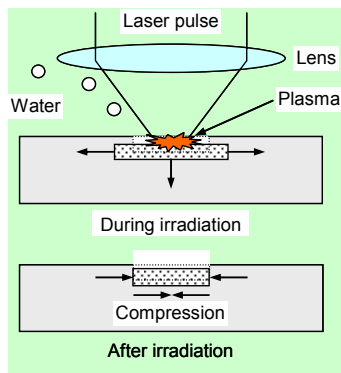


Fig.2 Mechanism for residual stress improvement using laser irradiation

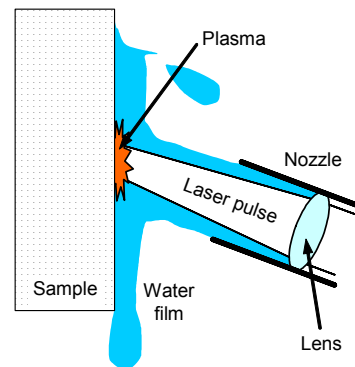


Fig.3 Laser peening accompanied by water flow from nozzle

small pulse energy that allowed an optical fiber to be used for the transmission line¹⁵⁾. The water film was approximately 0.1 mm thick; this was necessary for suppressing the plasma expansion. In the case of use in welded zones of bridges or other structures, this was achieved by irradiating with the laser while injecting water from the nozzle, as shown in **Fig. 3**. Thus, laser peening can be used in factories as well as on site.

3. Change of Residual Stress by Laser Peening

The residual stresses of the laser-peened base metal and the laser-peened boxing toe of the welded rib plate of high-strength steel (HT780) was measured to determine whether laser peening generated compressive residual stress on the surface. The measured values were compared with the residual stress on an unpeened specimen in order to identify the change of residual stress by laser peening.

3.1 Residual stress in parent metal

For two different production lots of the 9 mm thick high-strength steel (HT780-1 and HT780-2), the surface residual stresses were measured at the laser-peened spots and at the unpeened spots. **Tables 1** and **2** list the mechanical properties and chemical compositions of the two steels.

Laser peening of the high-strength steels are performed under the same conditions as those applied for the peening of SM490 steel. Pulse energy is 200 mJ, spot diameter is 0.8 mm, and irradiation density is 3600 pulse/cm²⁹⁾. The pitch of the pulse laser was 1/60 mm, and the stage with the specimen placed on it was moved. After the stage was moved by 10 mm, the process was reversed in order to have a line 1/60 mm below the irradiated area. The repetition of this process resulted in the irradiation of an area of 10 x 10 mm. The residual stress was measured by the X-ray diffraction (XRD, the $\sin^2 \phi$ method) obtained using Cr-K α (17 kV, 2.0 mA) as the X-ray source.

Table 1 Mechanical properties

	Mechanical properties			
	σ_Y (MPa)	σ_U (MPa)	δ (%)	YR (%)
HT780-1	789	842	19	94
HT780-2	804	823	21	95
Welding wire*	710	830	24	–

*: catalogue value

Table 2 Chemical composition

	Chemical composition (%)										
	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	B
	$\times 10^{-2}$	$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$
HT780-1	19	23	145	9	1	–	–	–	–	–	1
HT780-2	15	36	120	12	1	1	1	10	12	0	1
Welding wire*	8	38	125	9	11	–	222	–	63	–	–

$Ceq = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14$ *: catalogue value

Table 3 Results of residual stress measurement

	① without Laser peening		② with Laser peening		Change by Laser peening (②-①)	
	σ_x	σ_y	σ_x	σ_y	σ_x	σ_y
HT780-1	-44 ± 18	-35 ± 30	-174 ± 6	-312 ± 8	-131	-278
HT780-2	-6 ± 13	-70 ± 7	-191 ± 3	-330 ± 6	-185	-260

Table 3 lists the measurement results, where the values are the mean of the two spots. σ_x represents the residual stress component in the direction of the stage movement, while σ_y is the component perpendicular to this direction.

In Table 3, the most probable values calculated through the $\sin^2 \phi$ method and with confidence intervals (1σ) are listed after the \pm symbol. The confidence interval has a ± 30 MPa maximum but is mostly around ± 10 MPa. The spots that were not laser peened generated a compressive residual stress around -6 to -70 MPa for σ_x and σ_y , respectively. This stress was probably generated during the cooling process of the manufacturing process for the steel plate. As for the laser peened spots, significant compressive residual stress around -170 to -190 MPa was generated at σ_x , and -300 to -330 MPa at σ_y . Comparing the residual stress components σ_x and σ_y , the former tends to result in greater compressive residual stress. The phenomenon also seen in other materials during laser peening needs further investigation. The variation between the laser peened and unpeened spots is around 150 MPa at σ_x and about 270 MPa at σ_y , showing a significant change in residual stress towards the compressed side. These values confirm that the base metal in high-strength steel generates large compressive residual stress on the surface when peening conditions employed for SM490 are applied

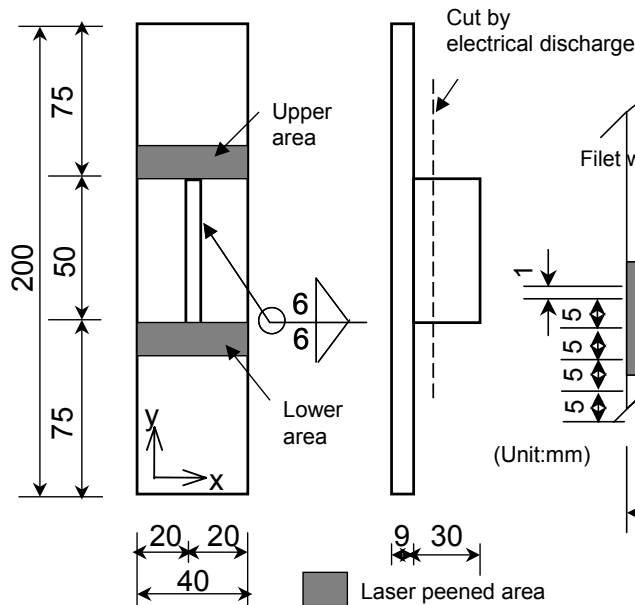


Fig.4 Specimen for residual stress measurement

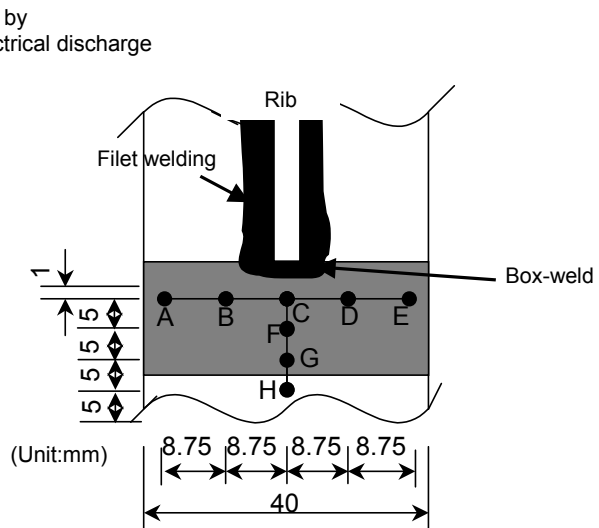


Fig.5 Measuring points of XRD

for the high-strength steel.

3.2 Residual stress in boxing toe

Figure 4 shows the shape and dimensions of the specimen, in which an all-round fillet (leg length: 6 mm) is welded to a 9 mm thick steel plate HT780-2, along with a 6 mm thick steel plate used as a rib. The 6 mm thick steel plate is obtained by reducing the thickness of HT780-2. CO₂ arc welding was employed and solid wire for the 780 MPa class steel was used as the welding material. Table 3 lists the catalogue values for the mechanical properties and chemical composition of the wire. The rib-plate was cut by electrical discharge at a height of 8mm, because the rib-plate disturbed residual stress measurement of a Y-direction stress component (σ_y) by XRD.

First, the residual stresses near the upper and lower boxing toes were measured. Then an area of 40 x 20 mm around the boxing toes was laser-peened and residual stresses at the same positions were measured. **Figure 5** shows points A–H, the positions where residual stresses were measured. Note that the conditions for irradiation and other factors are the same as in the case of the base metal, and the direction of moving the stage at irradiation is indicated in x in Fig. 4. **Figures 6** and **7** show the measurement results. σ_x is the residual stress component in the x direction (right angle to the rib), while σ_y is the residual stress component in the y direction (parallel to the rib). Before laser peening (indicated in \circ and \triangle), a compressive residual stress of around 100 MPa was measured at points A and E, which are close to the edges of the specimen, while the

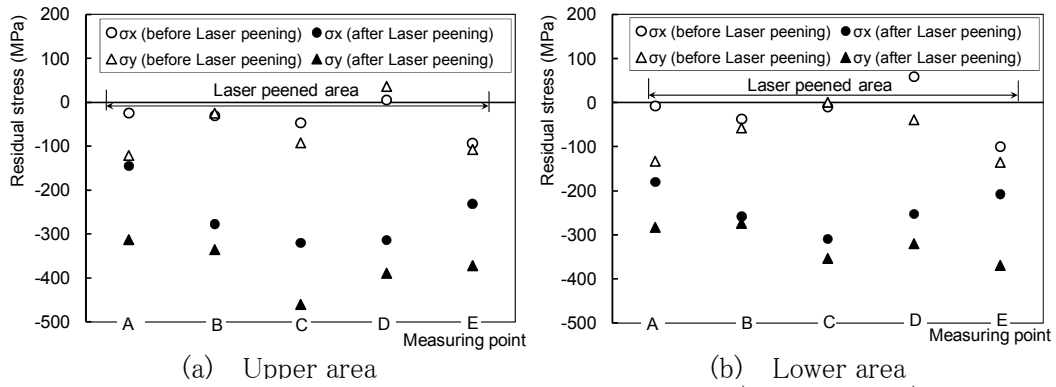


Fig.6 Results of residual stress measurement (A, B, C, D, E)

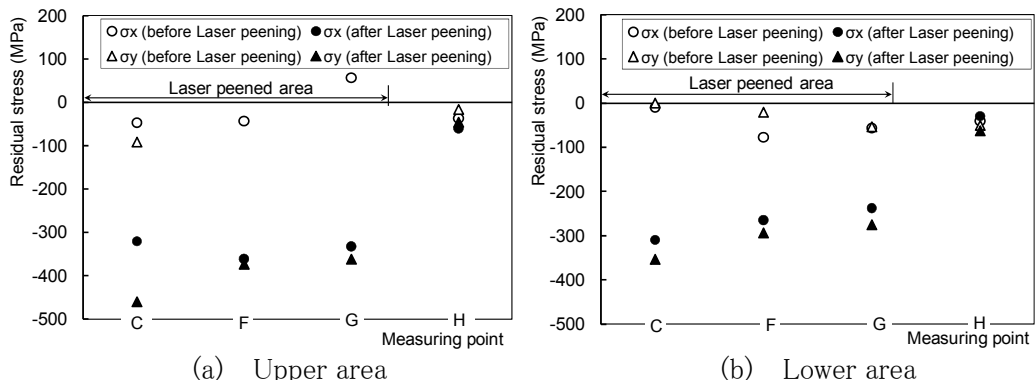


Fig.7 Results of residual stress measurement (C, F, G, H)

stress was measured to be 0 MPa at other points. After laser peening (indicated by ● and ▲), no change in residual stress was seen at point H (the unpeened point), whereas large compressive residual stresses between -150 and -450 MPa were measured at the laser-peened points (A-G). Further, the closer a point is to the weld toe, the greater is the change in the compressive residual stress. In particular, point C, which is closest to the toe where fatigue cracking is initiated, shows the largest change in residual stresses following laser peening. It is therefore estimated that significant compressive residual stress is also generated near the boxing toe.

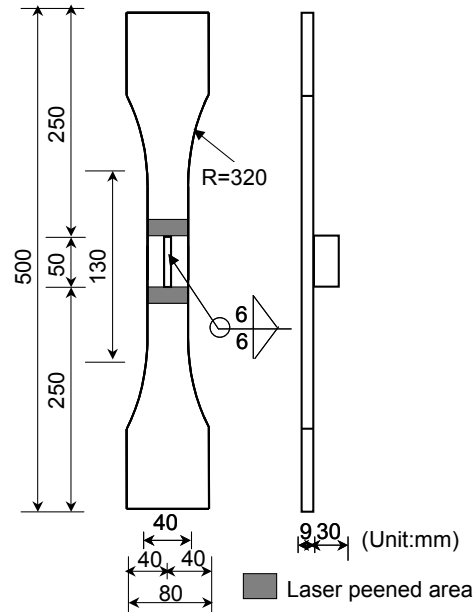


Fig.8 Specimen for fatigue test

4. Effect of Laser Peening on Fatigue Life

Fatigue tests were performed on laser-peened and unpeened specimens for a quantitative investigation to determine whether fatigue life in the boxing toe of high-strength steel prolonged by laser peening.

4.1 Experiment overview

Using the 300 kN uniaxial fatigue testing machine, a fatigue test was performed in constant stress ranges for the unpeened specimen (hereafter, called NP) and the laser-peened specimen (hereafter, called LP).

Figure 8 shows the shape and dimensions of the specimen in which an all-round fillet (leg length: 6 mm) is welded to a 9 mm thick plate, along with a 6 mm thick steel plate used as a rib. The steel material and welding conditions and materials are as mentioned in Section 3.2. The conditions, positions, and the laser-peened area are also the same as mentioned in Section 3.2.

Figure 9 shows the specimen shape and the laser-peening location. For the stress range to be loaded, there are three NPs at 200 MPa, three at 250 MPa, two each at 300, 350, 400, 450, 500, 550, and 600 MPa, making a total of 20 specimens; there are two LPs each at 300, 350, 400, 450, 500, and 600 MPa, one at 550 MPa, making a total of 13



Fig.9 Photograph of a box-welded rib specimen and its laser-peened area

specimens. The stress ratio was 0, and the censored limit was set at 10^7 times.

4.2 Experiment results

Figure 10 shows the S-N diagram obtained from the experiment. The arrows in the figure indicate that the number of censored limits of fatigue life is 10^7 times. The following sections will describe the experimental results in terms of crack-initiation positions, fatigue limit, and fatigue life.

4.2.1 Fatigue crack initiation position

Figure 11 shows photographs of the rupture surfaces. The mark ● in the figure represents the crack-initiation position, while the arrows show the direction in which cracking propagate. In the case of all NPs, crack initiation occurred at the boxing toe, where stress concentration exists. In the case of LPs exceeding 450 MPa, crack initiation occurred at the boxing toe as a result of stress concentration. However, in the stress range between 350 and 400 MPa, cracks were initiated at unpeened back side of the boxing toe, where stress concentration does not exist, instead of at the laser-peened toe.

The experiment revealed that the application of laser peening to the boxing toe accounts for the changes in the crack initiation positions owing to the differences in the stress ranges, and cracks initiate from the back side in relatively small stress ranges.

4.2.2 Fatigue limit

Three NPs in the 200 MPa stress range and one out of three in the 250 MPa range reached the censor limit of 10^7 times; the remaining two NPs in the 250 MPa range fractured at around 7×10^5 times and 26×10^5 times. This indicates that the fatigue limit of an unpeened specimen is 200 MPa.

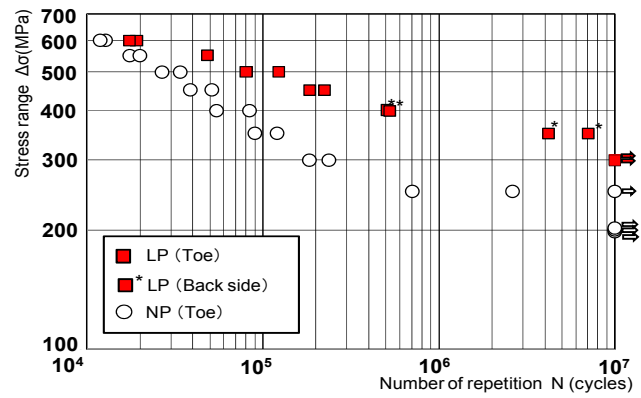


Fig.10 S-N diagram



(a) NP
(All stress ranges)

(b) LP
($\Delta \sigma = 350$ and 400 MPa)

(c) LP
($\Delta \sigma = 450 - 600$ MPa)

Fig.11 Fracture surface

On the other hand, two LPs reached the censor limit of 10^7 times in the 300 MPa stress range and fractured after around 42×10^5 times and 7×10^6 times in the 350–MPa range. Therefore, the fatigue limit of the laser-peened specimen is 300 MPa. Further, cracks did not initiate from the toe but from the back side in the 350–400 MPa stress range, illustrating the possibility that the fatigue limit of a laser-peened toe is 350 MPa or more.

Thus, the fatigue limit of the boxing toe in the high-strength steel increased from a stress range of 200 MPa to at least 300 MPa, i.e., by at least 1.5 times, as a result of laser peening.

4.2.3 Fatigue life

Figure 12 shows a comparison between the fatigue lives of NPs and LPs in each stress range. The vertical axis represents how many times the fatigue life of each LP is longer when the average fatigue life of two NPs in each stress range NP_{AVE} is set to 1. The arrows in the figure show that the fatigue life exceeded 10^7 times. The fatigue life was 1–1.5 times greater in the extremely high stress range of 600 MPa, indicating the reduced effect of laser peening. However, the fatigue life improved by more than 2.5 times in the 550–500 MPa range. In addition, the smaller the stress range is, the more significant is the improvement in the fatigue life, indicating that a fatigue life is at least 50 times greater in the 300 MPa stress range.

These results confirmed that laser peening of the boxing toe in high-strength steel does not improve the fatigue life in the 600 MPa stress range while it prolonged the fatigue life by approximately 2.5–50 times or more in the 300–550 MPa stress range. This remarkably extended the fatigue life of the boxing toe. It was further revealed that the smaller the stress range, the greater was the improvement in the fatigue life.

5. Conclusions

- (1) Large compressive residual stress was generated on the base metal surface of the high-strength steel (HT780) under the peening conditions employed for SM490.
- (2) Laser peening generated significant compressive residual stress at the boxing toe of the high-strength steel, where fatigue cracking is initiated.
- (3) In the laser-peened boxing toe specimen of the high-strength steel, the initiated cracks varied depended on the stress range. For small stress ranges, cracks were initiated from the back side of the toe where no stress concentration was observed.
- (4) The fatigue limit of the boxing toe of the high-strength steel was improved by at

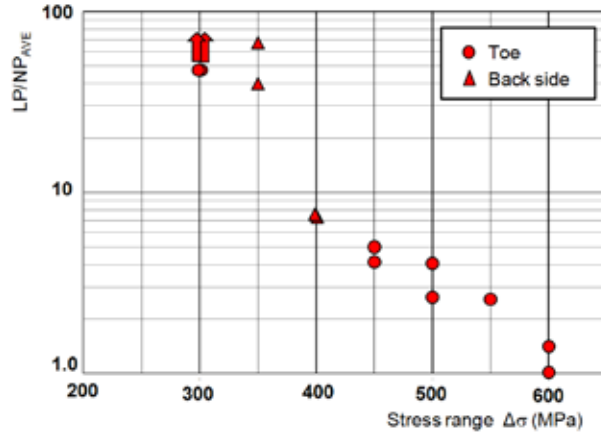


Fig.12 Comparison between NP and LP

least 1.5 times as a result of laser peening.

- (5) The smaller the stress range, the greater was the improvement of the fatigue life of the high-strength steel boxing by laser peening. The fatigue life in the stress range between 300 and 550 MPa was prolonged by approximately 2.5– 50 times or more compared to the unpeened specimen.

Taking these points into consideration, it was concluded that laser peening of the boxing toe of the high-strength steel (HT780) generated significant compressive residual stress, which remarkably extended the fatigue life of this part¹⁶⁾.

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