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HAZ Softening-Resistant High-Strength Steel Tubes for Automobile Propeller Shafts

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Abstract:

Automobile propeller shafts made of electric resistance welded (ERW) steel tubes with both ends welded to adjoining parts are repeatedly subjected to torques developed by the automobile during acceleration and deceleration. High fatigue strength is therefore required of these ERW tubes including welds. In order to reduce the weight of propeller shafts, the material steel tubes must be enhanced in the fatigue strength of not only the base metal but also the weld metal. To meet this requirement, a new high-strength ERW tube steel was developed that ensures high fatigue strength in the heat-affected zone (HAZ) of welded joints as well. The new ERW tube steel can be joined by friction welding that is noted to have the effect of reducing the noise of propeller shafts.

1. Introduction

In recent years, much development effort has been expended to accomplish automobile weight reduction and fuel economy enhancement from the standpoints of global environmental protection and economics. Steel tubes with tensile strength ranges of 440 to 540 and 690 to 780 N/mm^2 [1-3] have been used to reduce the diameter and wall thickness, hence the weight[4-6], of propeller shafts while satisfying the acceleration performance and acoustic requirements. This report gives an outline of the propeller shaft, describes the measures taken to improve the fatigue strength of propeller shaft welds as a means of reducing the shaft weight, and introduces the quality characteristics of Nippon Steel's electric resistance welded (ERW) steel tube for propeller shafts, including some information about application and fabrication techniques.

2. Description of Propeller Shafts

The propeller shaft is a drive shaft for front-engine, rear-drive automobiles. It is a critical component that rotates at high speed while responding to axial dimensional changes and angular variations under changing road impact and vehicle load, and receiving the engine torque that constantly fluctuates. It is composed of various parts according to the specific construction of the automobile. Generally, the resonance vibration region of a rotating shaft depends on its characteristic properties. In order to make it higher than the normal rotation region, the propeller shaft is generally made of a carbon steel tube of high torsional or flexural rigidity relative to its mass, and is composed of spline shafts, universal joints and center bearings[7].

Fig. 1 shows a typical propeller shaft production process at automobile manufacturers[7]. Bold lines indicate the production process of Nippon Steel's ERW steel tubes. The ERW tube is cut to length, has joint yokes welded and other parts assembled, and is adjusted as to rotational runout. The propeller shaft assembly must be able to withstand static and dynamic torques and be well balanced. The shear stress ($\tau_{0.2}$) or yield torque ($T_{0.2} = \tau_{0.2} \times Z_p$) of the tube is proportional to the yield strength of the tube steel as shown in **Fig. 2**. As evident from the appearance of a propeller shaft after static torsion testing in **Photo 1**(a), the maximum torsional torque is dictated by the buckling of the tube. The static torsional strength of the propeller shaft can thus

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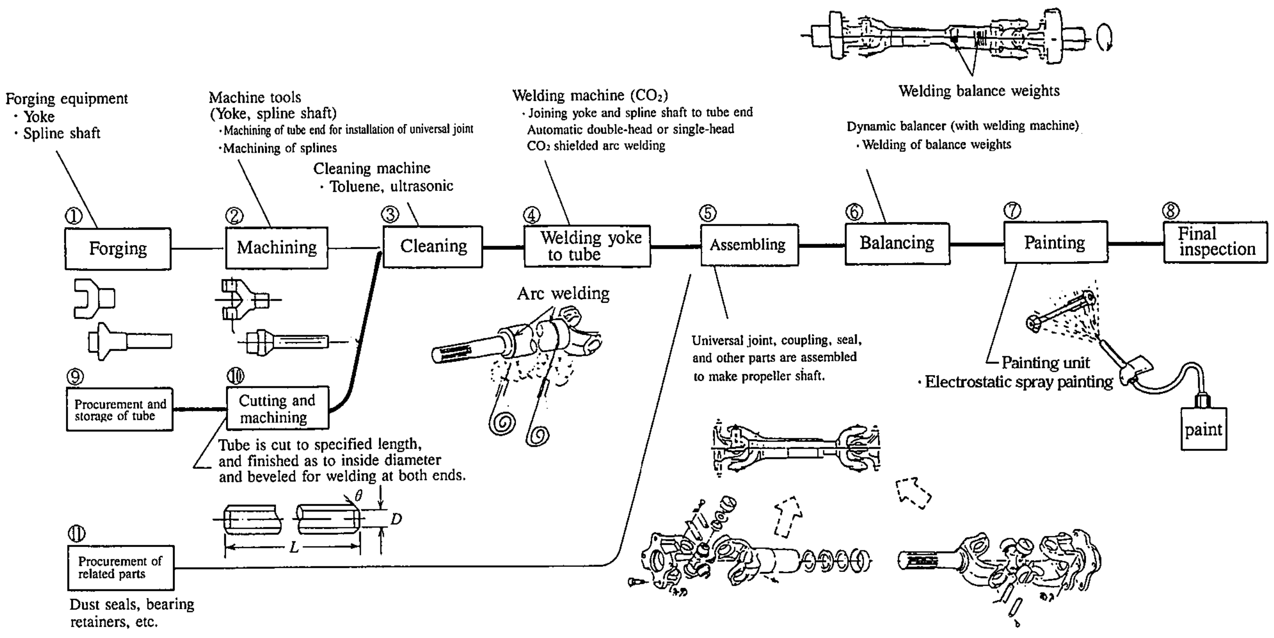


Fig. 1 Typical propeller shaft production process[7)]

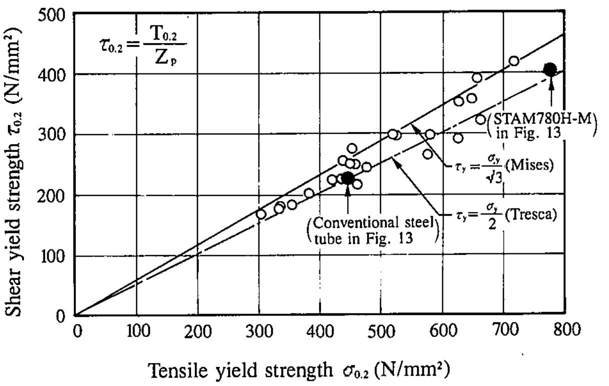
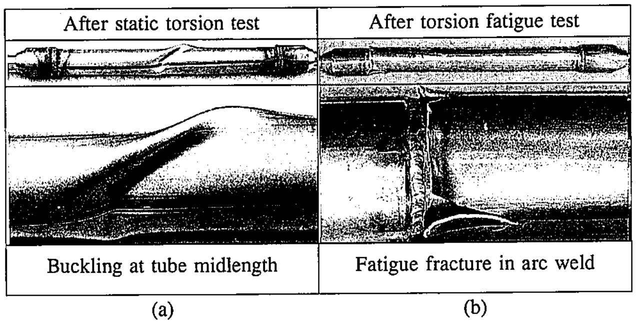


Fig. 2 Relationship between tensile strength and shear (or torsional) strength in ERW tubes



(a) (b)

Photo 1 Appearance of sample tubes after torsion test (75.0 mm ϕ ×1.6 mm t)

be enhanced by increasing the strength of the material tube. **Photo** 1(b) shows the fatigue fracture of a propeller shaft after torsional fatigue testing. The dynamic torsional strength of the propeller shaft depends on the fatigue fracture strength of the yoke welded joint. To reduce the weight of the propeller shaft, improvements must be made in the material steel strength as well as in the propeller shaft strength including the fatigue strength of welds.

As the method for welding the universal joint yoke to the steel tube, friction welding is recently drawing keen attention over the conventional arc welding. The high joining accuracy of friction welding assures good balance during high-speed rotation and reduces automobile noise[4,5)]. Formerly, friction welding was easily applied to thick-walled tubes but was considered difficult to apply to such thin-walled tubes as propeller shaft tubes[8)].

Photo 2 shows the friction welds of thin-walled (low-t/D) ERW tubes of different strengths. The tubes were gripped by collet chucks with a projection of 10 mm each. The ratio of friction welding pressure (P1) to forging pressure (P2) was fixed at 0.5 (P1/P2 = 1/2), and the forging pressure was changed. Since the friction upset distance was fixed at 3.0 mm, the total upset distance (or loss of length) measured to be 6.0 to 12.0 mm. When the forging pressure was low as shown in the bottom row of **Photo** 2, the joining accuracy was good. When the forging pressure was increased as shown in the middle row of **Photo** 2, a mismatch developed between the outside surfaces of the tubes, and the joint interface was inclined. This is the maximum forging pressure allowed to produce a good friction weld. When the forging pressure was raised further as shown in the top row of **Photo** 2, the surface mismatch increased, the friction weld flash meandered in the circumferential direction, the tubes were flattened immediately near the weld flash, and the joining accuracy sharply declined. The left and right columns of **Photo** 2 show tubes of different yield strengths. The difference of yield strength produced a difference in the maximum forging pressure below which the joining accuracy does not deteriorate.

Fig. 3 shows the effects of the tube forging pressure and steel yield strength on the shape stability of friction welds produced in the friction welding test of tubes with different yield strengths, as shown in **Photo** 2. When the yield strength is low, the joining accuracy is low even if the forging pressure is low. With the use of high strength material, on the other hand, the

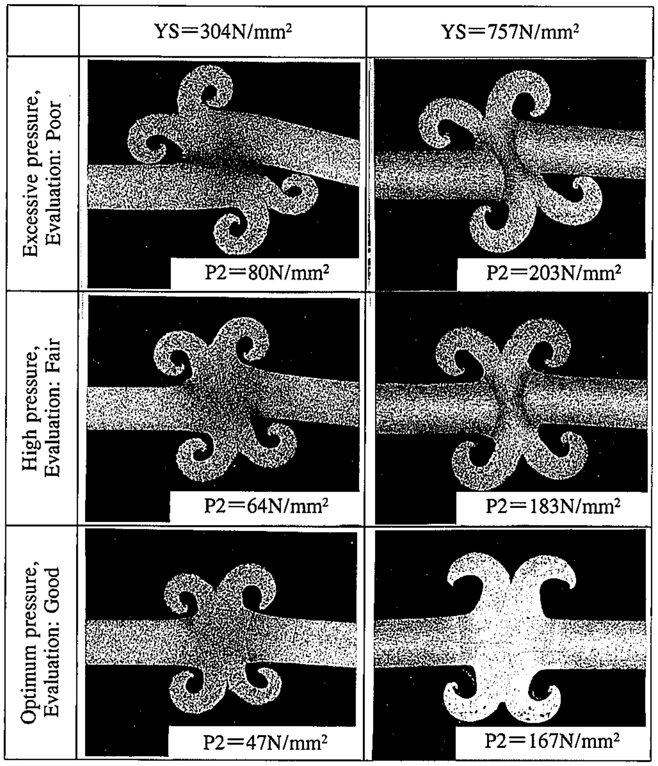


Photo 2 Cross-sectional shapes of friction welds in thin-walled tubes (75.0 mmϕ × 1.6 mm t, t/D = 0.021)

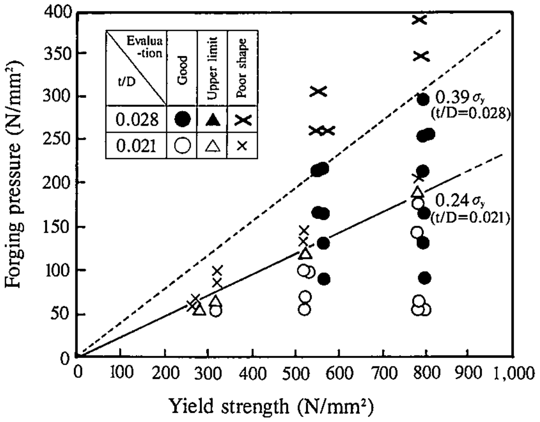


Fig. 3 Relationship between fiction weld stability and steel yield strength

region of good weld shape expands toward the high end of the forging pressure range. Given the stability of heat generation and the low axial force control limit of the friction welding machine, the optimum friction welding pressure is several tens of newtons per square millimeters[9]. When thin-walled tubes like propeller shafts are friction welded, there is a limit to the minimum yield strength of the material to be used. Relatively thin-walled tubes can be successfully friction welded if they are made of high-strength steel.

3. Fatigue Properties of Welds

Generally in changing the material of a welded structure from mild steel to high-strength steel, due attention must be paid to the fatigue failure of welds in the structure[10]. **Fig. 4** shows the fatigue strength under pulsating tension of butt welded joints[10]. The fatigue strength of welded joints cannot be easily enhanced by raising the steel yield strength above the range of 440 to 540 N/mm². This is attributable to the effects of stress concentration, residual stress, and quality change in the welded joint[10]. **Fig. 5** comparatively shows the cross-sectional hardness distribution of butt welded joints of low-strength and high-strength steels. In the low-strength steel, the drop of hardness of the butt welded joint is slight compared with that of the base steel. In the high-strength steel, on the other hand, the decrease of hardness is significant, with the hardness of the HAZ sometimes falling close to that of the low-strength steel. Strengthening through the introduction of forming strain (dislocation) is indispensable for as-rolled ERW tubes, which, however, is apt to cause a loss of strength in the HAZ.

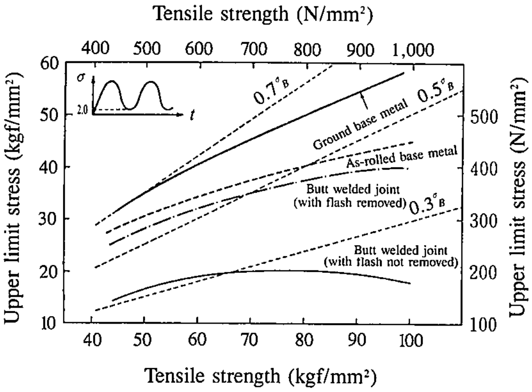


Fig. 4 Fatigue strength under pulsating tension (2 × 10^6) of base metal and butt welded joints for ERW tube steels[10]

Material factors responsible for the fatigue strength of welds were studied then. ERW tubes with different degrees of hardness drop in the HAZ as shown in **Fig. 6** were fabricated into propeller shafts as illustrated in **Fig. 7**. These prototype propeller shafts were tested for fatigue strength under completely reversed torsion. The test results are shown as relationship between the hardness of the most softened zone and the fatigue strength of the welded joint in **Fig. 8**. The ERW tubes A and B both exhibited the hardness of about 250 Hv in the base metal and high fatigue strength. Neither friction welding (FW) or arc welding (AW),

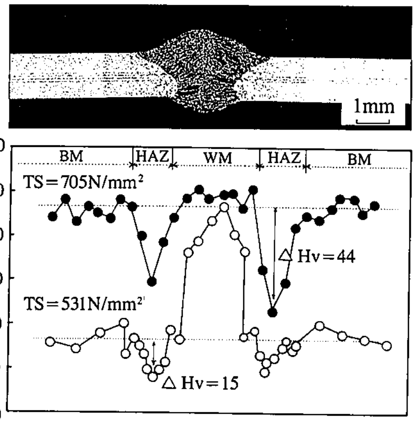


Fig. 5 Hardness distribution of arc welded joints

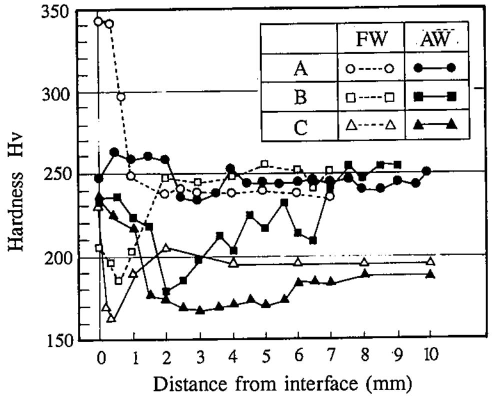


Fig. 6 Hardness distribution of tube welded joints

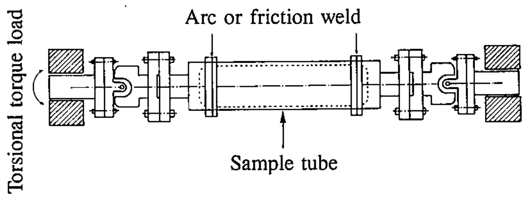


Fig. 7 Torsion fatigue test method for propeller shaft tubes, including welded joints

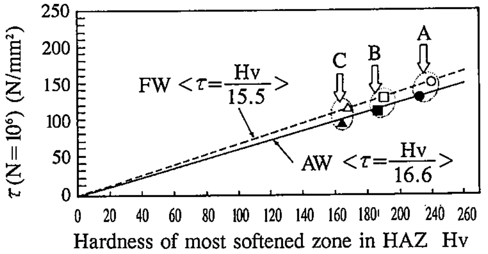
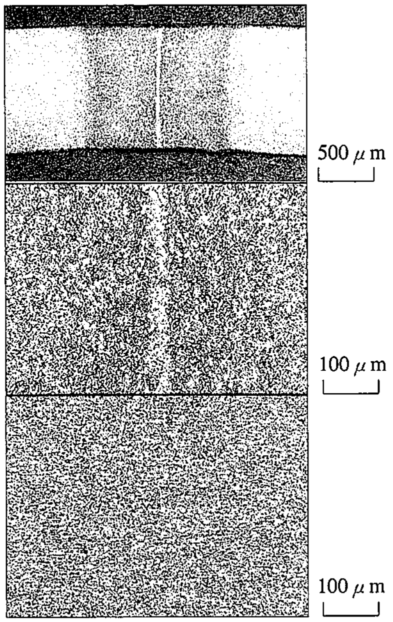


Fig. 8 Relationship between hardness of most softened zone and fatigue limit


(a)Electric resistance weld

(b)Electric resistance weld

(c)Base metal

Photo 3 Microstructures of HAZ softening-resistant high-strength steel tube (STAM780H-M, 65.0 mm ϕ × 1.6 mm t)

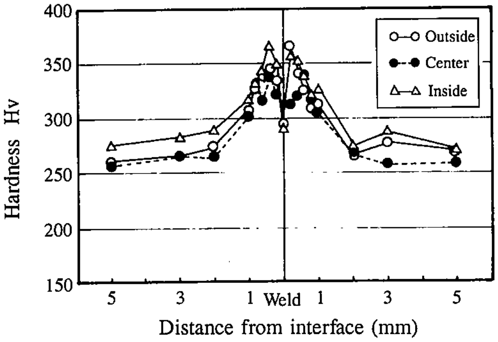


Fig. 9 Hardness distribution of electric resistance weld

however, imparted fatigue strength equivalent to the base metal hardness to the ERW tube B with severe softening of the HAZ. For the ERW tube A with lessened base metal softening, on the other hand, the 10^6-cycle fatigue limit varied with the hardness of the softened zone and, thus exhibiting high torsional fatigue strength.

4. HAZ Softening-Resistant Electric Resistance Welded (ERW) Steel Tubes for Propeller Shafts

Nippon Steel's Nagoya Works produces ERW steel tubes for important parts of automobiles and other vehicles such as propeller shafts, by combining high-quality steel from an integrated iron and steel production process with excellent ERW tube manufacturing technology. In more detail, steel is made by advanced refining technology, rolled into strip by a thermomechanical control process (TMCP) at the hot strip mill, electric resistance welded into tubes featuring sound weld quality, machined to remove inside beads, and inspected for delivery by a rigid quality inspection system.

HAZ softening-resistant high-strength steel tubes with enhanced weld fatigue strength as shown for A in **Fig.** 8 are manufactured focusing attention on the steel strengthening mechanism for the HAZ, namely, optimally adjusting the trace element composition in the steelmaking stage, employing the TMCP at the hot strip mill, and optimizing the roll forming pattern at the tube mill. The properties of the new 780-N/mm² HAZ softening-resistant high-strength ERW tube steel, designated STAM780H-M, are introduced below.

4.1 Microstructures and hardness

Photo 3 shows the transverse microstructure of the new ERW tube steel. The low-magnification microstructure of the tube near the weld is shown in **Photo** 3(a), the high-magnification microstructure of the tube near the weld in **Photo** 3(b), and the high-magnification microstructure of the base metal in **Photo** 3(c). The base metal has a fine-grained ferrite-pearlite microstructure. The weld has a heat-affected zone of the same width as the tube wall thickness because of thermal hysteresis during the welding, and exhibits a fine-grained microstructure as does the base metal. A ferrite-rich bond is formed in the central portion of the weld. This is an indication of weld metal fusion during electric resistance welding.

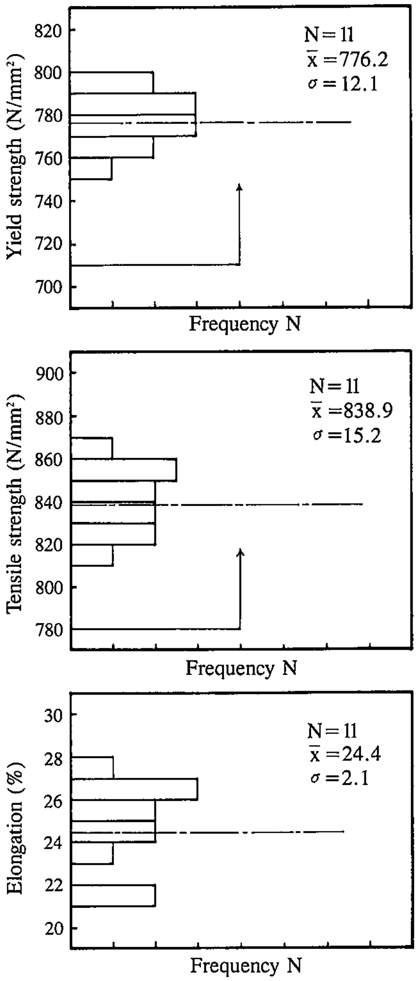


Fig. 10 Results of tensile test (STAM780H-M, 65.0 mm ϕ × 1.6 mm t)

Fig. 9 shows the hardness distribution of an electric resistance weld. The heat-affected zone (HAZ) is harder than the base metal, but not exceeding a maximum hardness of about 370 Hv.

4.2 Tensile strength

Results of tensile test conducted on JIS No. 11 specimens are given in **Fig. 10**. The specified values are indicated by arrows. As for tensile strength, for example, values greater than the specified value of 780 N/mm² are stably obtained.

4.3 Properties of arc weld

Photo 4 and **Fig. 11** respectively show the cross-sectional microstructure and hardness distribution of a 2.6-mm wall ERW tube arc welded (YM-80C, 1,2 mm ϕ, 3.2 kJ/cm) to a universal joint yoke-equivalent part (S35C). The HAZ is as hard as the base metal.

4.4 Properties of friction weld

Photo 5 and **Fig. 12** respectively show the cross-sectional microstructure and hardness distribution of a 1.6-mm wall ERW tube friction welded (P1/P2 = 0.5, P2 = 100 N/mm², UT = 10 mm[9], outside surfaces flush) to a universal joint yoke-equivalent part (S35C, 2.2 mm t). The tube and yoke exhibit almost the same hardness rise near the friction weld interface, but the drop of hardness at the toe of the tube weld flash is small. This means that the friction weld is kept at the same hardness as the base metal.

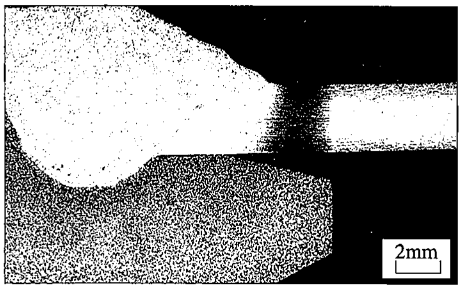


Photo 4 Cross section of arc weld (t = 2.6 mm)

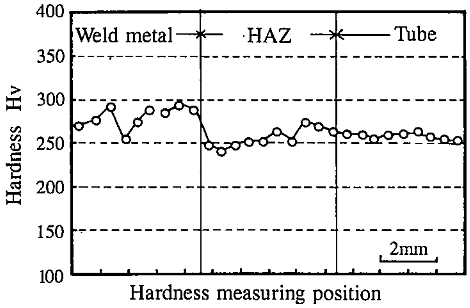


Fig. 11 Hardness distribution of arc weld

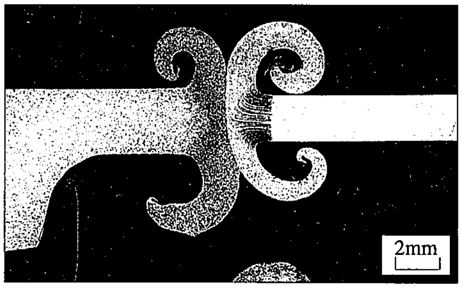


Photo 5 Cross section of friction weld (t = 1.6 mm)

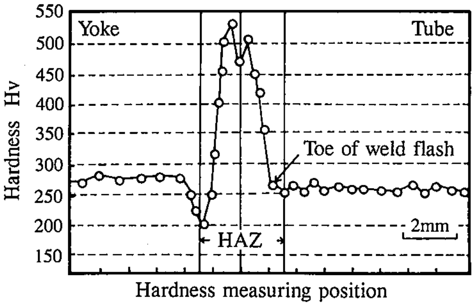


Fig. 12 Hardness distribution of friction weld

As described in Chapter 2, friction welding yields such high joining accuracy that it is drawing attention as an excellent process assuring low noise[4,5]. The joint geometry of HAZ softening-resistant high-strength steel tubes is discussed here. The joint shape of the friction weld depends mainly on the forging pressure (P2). **Fig. 13** shows the relationship of the forging pressure with the faying surface area ratio (t_w/t_0), radius of curvature of the weld flash toe (ρ), total upset distance, and rotational

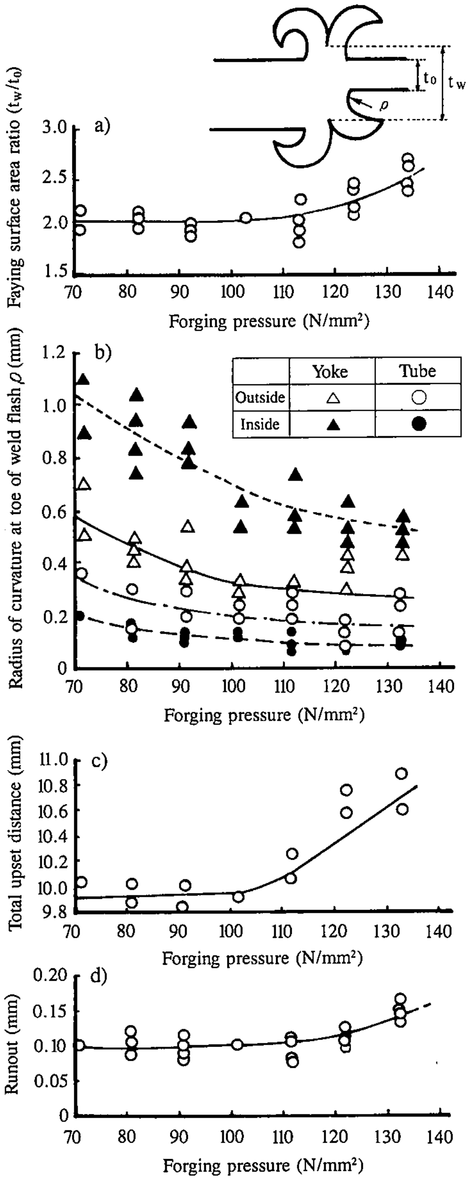


Fig. 13 Relationship of forging pressure with friction weld geometry

runout detected in the tube at 10 mm from the friction weld interface when the forging pressure is changed relative to the friction welding conditions shown in **Photo 5**. Increasing the forging pressure increases the faying surface area ratio and decreases the radius of curvature of the weld flash toe. The curve indicating the increase in the faying surface area ratio and the curve indicating the decrease in the radius of curvature of the weld flash toe change in slope where the forging pressure is about 100 N/mm^2. The forging pressure region can be divided into two parts at the boundary of about 100 N/mm^2. The upsetting deformation is mainly absorbed by the deformation of the HAZ (decrease in the radius of curvature of the weld flash toe) in one region and by the deformation of the weld interface (increase in the faying surface area ratio) in the other region. As the forging pressure rises above 100 N/mm^2, the total upset distance increases and at the same time, the rotational runout slowly increases. This means that the forging pressure should preferably be set at less than 100 N/mm^2. The rotational runout can be reduced below 0.15 mm by controlling the forging pressure at such a low level.

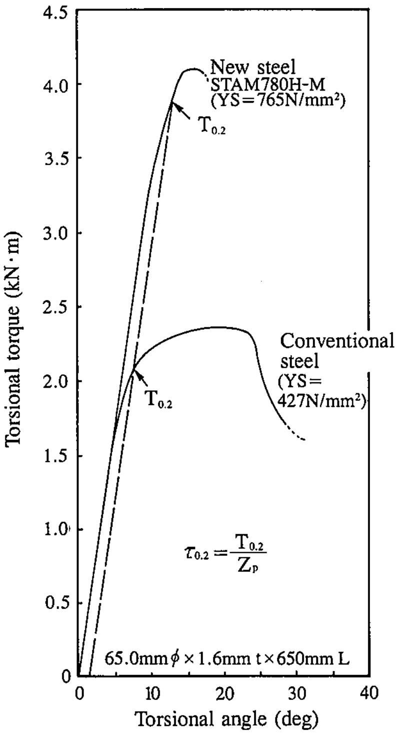


Fig. 14 Comparison in static torsional properties of new steel and conventional steel

To estimate the effect of weld flash toe shape on fatigue, the stress concentration factor of the weld flash toe was calculated by the finite element method (FEM). The stress concentration factor of the weld flash toe is about 1.4[3] in the forging pressure range of 70 to 100 N/cm^2 where good joining accuracy is obtained. In this range, the forging pressure has only a small effect on the stress concentration factor.

4.5 Static torsional strength

Fig. 14 gives the static torsion test results of the new ERW tube steel STAM780H-M as compared with a conventional ERW tube steel. The torsional torque of each grade rises until the buckling of the tube at the midlength. The yield torque ($T_{0.2}$) is indicated by arrows in **Fig. 14**. The torsional strength increases with increasing yield strength. The relationship between the shear yield strength derived from the yield torque and the tensile yield strength is the same as shown in **Fig. 2**.

4.6 Torsional fatigue strength

Propeller shaft-equivalent parts were fabricated by arc or friction welding and torsion tested in the manner shown in **Fig. 7**. High fatigue strength as shown in **Fig. 15** was obtained by alleviating the drop of hardness in the HAZ. **Photos 6** and **7** respectively show the cross-sectional microstructures of arc welded and friction welded test specimens near the initiation sites of fatigue fracture. In each case, the new ERW tube steel cracked at the toe of the arc or friction weld.

5. Conclusions

HAZ softening-resistant high-strength ERW steel tubes have been developed to improve the fatigue strength of weld metal in

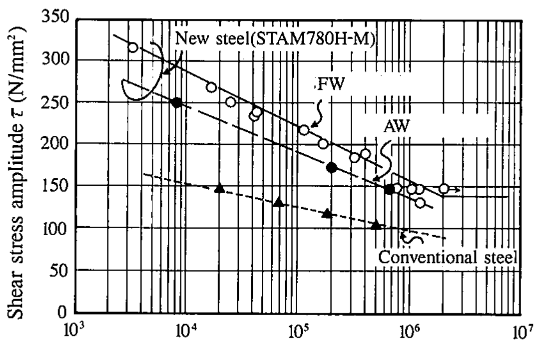


Fig. 15 S-N curves of prototype propeller shafts

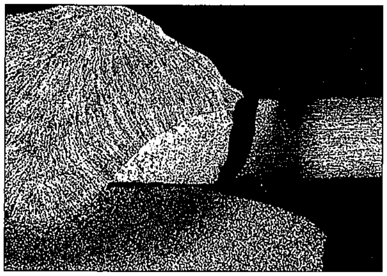


Photo 6 Fatigue fracture of arc weld

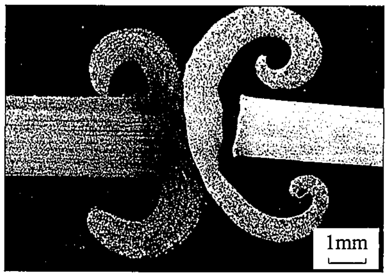


Photo 7 Fatigue fracture of friction weld

the as-welded condition. Friction welding, highlighted as an attractive joining method in the automobile propeller shaft production process, has been shown to produce welded joints with close dimensional tolerances and high fatigue strength. The HAZ softening-resistant high-strength ERW tubes can be used to save the weight of propeller shafts whose weight reduction has so far been constrained by the fatigue fracture of welded joints.

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