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High Performance Steel Tube for Automotive Parts†

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Abstract:

JFE Steel has newly developed two kinds of steel tubes having excellent fatigue endurance for automotive suspension parts. The tube employed to torsion beam has an excellent combination of fatigue endurance, hydro-formability and delayed fracture resistance. These properties can be obtained by the low C (less than 0.3%) based chemistry and the high precision controlled rolling and cooling technique in hot rolling. Further developed steel tube for stabilizer exhibits also excellent fatigue endurance induced from its high r-value (more than 1.5) property. This excellent crystallographic characteristics can be obtained by the warm reducing in the "HISTORY" process and contribute to improve the fatigue life by suppressing the wall thickness reduction during bending applications. Moreover, JFE Steel has been promoting the application of steel tube to automotive suspension parts, with not only newly developed steel tubes mentioned above, but also with the analysis of the formability of high strength tube in rotary draw bending process and the development of the related new rotary bending method without both mandrel and wiper.

1. Introduction

Automotive parts made of steel sheet, steel bar, or forged steel have often been substituted with hollow parts made of steel tube in recent years, as an effective way of simultaneously reducing the car body weight to improve fuel consumption and of strengthening the car body for occupant protection.

The steel tubes for these parts are requested to have higher performance than ever, including the ability to withstand extremely severe plastic working, even though they are high strength steel tubes and high carbon steel tubes.

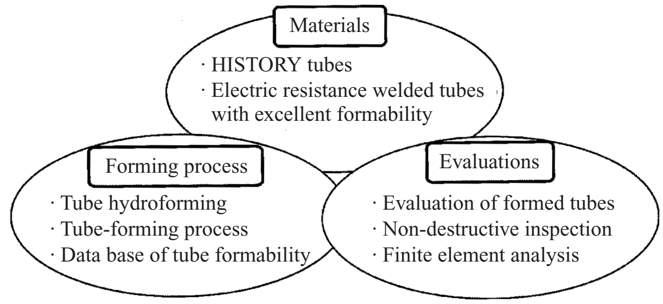

Fig. 1 Schematic description of correlated development items for tube applications to automotive structural parts

With this background, JFE Steel has developed suitable steel sheet base materials and processes for manufacturing steel tubes, and has developed high performance steel tubes including 780 MPa class excellent formability electric resistance welded (ERW) steel tubes[1)], and excellent formability and high dimensional accuracy HISTORY steel tubes[2)]. In addition to these high performance steel tubes, JFE Steel has flexibly combined secondary tube-forming technologies such as bending of high strength steel tubes and techniques for evaluating the performance of steel tubes, shown in **Fig. 1**, thereby developing steel tube products for automotive torsion beams, stabilizers, and lower arms.

This paper describes the recent development of these products.

2. Steel Tube for Quench Type Torsion Beams

To reduce the weight and size of suspension parts, steel tubes have increasingly been used in recent years as the base material as they have high rigidity and a closed-

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cross section to the torsion beam suspension[3–5]. When particularly high static strength and fatigue enclurance are required, strengthening by quenching is effective. However, the forming of unequal section in torsion beam requires hydro-formability and press-formability, both of which counteract the strength increase. Furthermore, weldability, phosphatability, low temperature toughness, hydrogen embrittlement resistance, are also important characteristics for practical applications. This section describes the material characteristics of steel tubes for quench type torsion beams, developed to provide the above necessary characteristics.

2.1 Effect of Strength and Microstructure on the Torsional Fatigue Endurance

The effect of strength and microstructure on the fatigue endurance was evaluated using a laboratory vacuum-fused material having a composition of 0.1–0.2%C-0.4%Si-1.9%Mn-0.2%Cr-0.2%Mo-0.01%P-0.001%S. The prepared ingot was hot-rolled, and one hot-rolled sheet was then heated to an austenite-ferrite two-phase region, while another one was heated to an austenite single-phase region in a salt bath, each of which was immediately quenched by water, and then was tempered. Using their round bar specimens of 6 mm in diameter at parallel portions, torsion fatigue characteristics were evaluated under a stress ratio of −1 and repetition rate of 33 Hz.

Photo 1 shows microscopic structures after heat treatment. The material heated to the austenite-ferrite two-phase region shows the ferrite and martensite structure, while the material heated to the austenite single-phase region shows the martensite structure. The ferrite and pearlite structure is a material in the as-hot-rolled state for comparison.

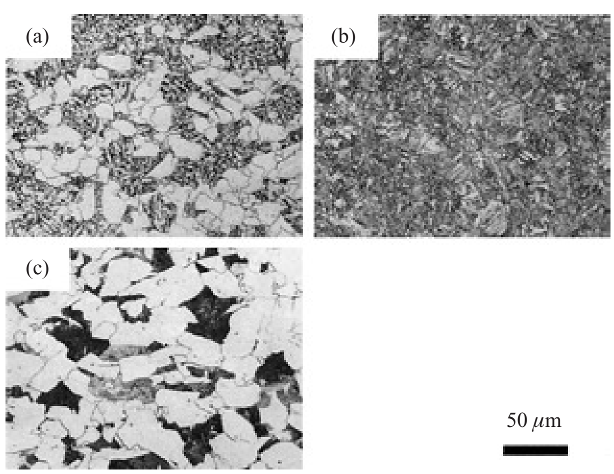


Photo 1 Optical micrographs of heat treated specimens for torsion fatigue test ((a) Ferrite and martensite; TS = 920 MPa, (b) Martensite; TS = 1 380 MPa, (c) Ferrite and pearlite; TS = 540 MPa)

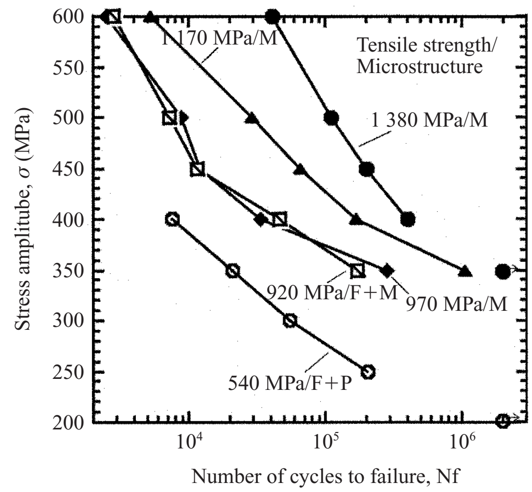


Fig. 2 Fatigue endurance (S-N) curves of high tensile steels under completely reversed torsion

Figure 2 shows the relation between the stress amplitude and the fatigue endurance in the torsional fatigue test. The fatigue strength monotonously increased with the increase of tensile strength in the range from 540 to 1 380 MPa. For suppression of crack initiation, a martensite structure containing no soft ferrite structure, is expected to be effective, while for fatigue crack propagation resistance, the ferrite and martensite structure is expected to be effective because of the stress relief by plastic deformation at the front of the fatigue crack[6]. Nevertheless, the martensite structure and the ferrite and martensite two-phase structure, both having a tensile strength of about 950 MPa, showed almost the same fatigue endurance, independent of the stress level. Based on the above torsional fatigue test result, martensite was adopted as the basic structure as it offers advantages in formability, phosphatability, low temperature toughness, while providing high strength with smaller amounts of alloying elements.

2.2 Effect of Hardness and Microstructure on Low Temperature Toughness and Hydrogen Embrittlement Resistance

The steel tube for torsion beams has a higher strength region of the base material, though different from high tension bolts, a steady tensile stress beyond the yield point is not applied. Therefore, the hydrogen embrittlement resistance was evaluated by a four-point bending test in dilute hydrochloric acid. A laboratory vacuum-fused material having the chemical composition of 0.14–0.2%C-0.3%Si-1.5%Mn-0.01%P-0.001%S-(Cr,Mo), with the carbon equivalent reduced to 0.6% or less as specified by Japanese Industrial Standards (JIS), was hot-rolled, and heated to an austenite single-phase region, then immediately quenched by water, and tempered. The thus treated material was fabricated to a 2 mm V-notched Charpy specimen, which was tested

Table 1 Charpy impact properties and delayed fracture resistance

HV10	Charpy impact properties		Delayed fracture resistance
	vE_0 (J/cm^2)	vTrs (°C)	Time to fracture (h)
431	113	−100	>240
454	103	− 80	>240

HV10: Vickers hardness obtained using a 10 kgf force
vE_0: Charpy absorbed energy at 0°C
vTrs: Charpy fracture appearance transition temperature

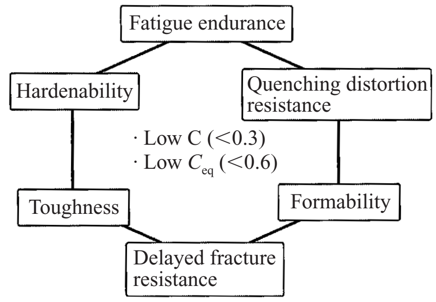
to evaluate the impact characteristics, and further was fabricated to a four-point bending specimen to conduct the four-point bending test[7] under a loading stress of 1 180 MPa in 1 N-hydrochloric acid.

Table 1 shows the Charpy impact characteristics and the four-point bending test results. All the tested specimens showed good impact characteristics, giving 80 J/cm^2 or higher absorbed energy at 0°C, and −60°C or lower fracture appearance transition temperature. The four-point bending test in 1 N-hydrochloric acid produced no crack over 240 h, showing excellent hydrogen embrittlement resistance.

Observation of microstructure by SEM showed that all the tested specimens had precipitation of fine carbide in the martensite lath. It is clarified that similar with the case of ultra-high strength water-quenched cold-rolled steel sheet[8], the low carbon equivalent, which proved that the low carbon martensite structure where carbide is finely dispersed, effectively gives excellent impact characteristics and hydrogen embrittlement resistance to the material.

2.3 Materials Design and Practical Characteristics of the Steel Tube for Quench Type Torsion Beams

While considering material variables for individual characteristics, JFE Steel has newly developed a steel tube for quench type torsion beams. **Figure 3** shows the characteristics required of the steel tube for torsion beams and the concept of materials design for the steel tube. That is, the amounts of carbon and carbon equivalent are limited to the necessary lowest level to secure stability of fatigue strength and hardenability, and the ferrite amount is assured by a combination with the technology of high precision controlled cooling in hot-



C_{eq}: Carbon equivalent; C+Mn/6+Si/24+Ni/40+Cr/5+Mo/4+V/14(JIS)

Fig. 3 Concept of developed steel tube for torsion beam

rolling, thereby establishing the formability which conflicts with hardenability and fatigue strength. The low carbon content and low carbon equivalent also improve the impact characteristics and hydrogen embrittlement resistance after quenching by suppressing the maximum hardness, and through the fine precipitation of carbide into the martensite lath. Furthermore, the increase in the martensite transformation temperature due to the lower carbon content and decreased carbon equivalent enhances the self-tempering of the martensite structure during the quenching stage and the paint baking stage, and so the additional tempering stage can be eliminated. In addition, the composition taking into account the arc-weldability and phosphatability is adopted, similar to the 780 MPa class steel tubes for suspensions and chassis[1]. Before real apprication, various tests to evaluate the hydrogen embrittlement resistance were performed, such as an electrochemical hydrogen charging test and corrosion fatigue test, in addition to the hydrochloric acid immersion test. Regarding the fatigue strength after quenching, it is important to consider the surface hardness distribution[9], surface roughness[10], and residual stress[11,12], other than the base material strength, in order to assure the stability.

Table 2 shows the characteristics of the newly developed steel tube for quench type torsion beams. Owing to the excellent characteristics of formability, hardenability, fatigue endurance, toughness, phosphatability, weldability, hydrogen embrittlement resistance, and quenching distortion resistance, it was proved through evaluation tests by customers that the steel tube is applicable to torsion beams. The developed steel tube is now used for automotive parts as shown in **Photo 2**.

Table 2 Typical properties of developed steel tube for quench type torsion beam

Formability, El (%) (JIS 12A)	Hardenability*	Fatigue endurance	Toughness, vTrs (°C)	Paintability	Arc weldability	Delayed fracture resistance**	Quenching distortion resistance
26	−30	Good	−80	Good	Good	No fracture	Good

El: Elongation, *Critical cooling rate from 950°C (°C/s), **Four-point bending test in 1 N HCl

Photo 2 Rear axle to which the developed steel tube for torsion beam is applied

3. HISTORY Steel Tube for Stabilizer

For automobile chassis parts such as stabilizers, which are made of steel bars, employing hollow materials using steel tubes have been conducted to attain both high strength and weight reduction[13]. These parts generally use high carbon steels having 0.20 to 0.45% C, and are subjected to heat treatment such as quenching and tempering after forming, thereby attaining high fatigue strength. Conventional high carbon ERW steel tubes, however, sometimes suffer problems in formability such as significant hardening at the seam welding portion and poor elongation. Furthermore, high strength of the base material hinders manufacturing, as it is difficult to roll-form heavy gauge and small diameter steel tubes in cold process, which is necessary in these parts. This problem becomes particular when the carbon amount is increased to attain high strength after heat treatment. HISTORY[2], which is JFE Steel's new technology for manufacturing ERW steel tube, effectively solves these problems. HISTORY steel tube is suitable for manufacturing heavy gauge and small diameter steel tubes because the small diameter product is manufactured from a large diameter mother tube by tube-reducing. Although a similar manufacturing method is already applied to seamless steel tubes and some ERW steel tubes[14,15], the HISTORY steel tube improves the formability by tube-reducing in a warm region where no steel tubes were treated, and tube-reducing is conducted using a newly developed four-roll reducer, thus manufacturing high precision heavy gauge and small diameter steel tubes[16]. This section describes the characteristics of high carbon HISTORY steel tube suitable for the parts subjected to bending, such as automobile stabilizer.

3.1 Bending Formability of HISTORY Steel Tube

Table 3 compares the tensile properties of high carbon steel (STKM 15A: 0.3%C-0.8%Mn steel) between HISTORY steel tube and conventional ERW steel tube. Compared with conventional ERW steel tube, HISTORY steel tube gives high uniform elongation (uEl) and total elongation (total El). The improvement is attained by eliminating work-hardening of HISTORY steel tube generated during cold roll forming of ERW steel tube through heating and warm-reducing. Another feature is that HISTORY steel tube has extremely high longitudinal Lankford value (*r*-value, ratio of sheet width distortion to sheet thickness distortion during tensile test: an index of the difficulty in reducing wall thickness). As shown in **Fig. 4**, HISTORY steel tube suppresses the reduction of wall thickness during bending compared with the conventional ERW steel tube. Accordingly, for parts such as stabilizers having a bending section, the use of HISTORY steel tube is expected to increase the fatigue strength. The high *r*-value of HISTORY steel tube is attained by the tube-reducing in a warm region (650°C to 900°C), and such a high *r*-value cannot be attained by a conventional ERW steel tube which is simply roll-formed from a steel sheet in cold process, nor by a steel tube which is manufactured by heat treatment of the above conventional ERW steel tube, nor by a steel tube which is formed by tube-reducing in a hot region. Through the warm-reducing, the rolling texture of RD//<110>, ND//<111>~<221>~<110>, specifically appearing during the tube-reducing, significantly develops and so increases the *r*-value[2,17]. This mechanism of increase in the *r*-value differs from the development of recrystallizing texture mainly in the ND//<111> orientation which is used to attain a high *r*-value in a steel sheet. Therefore, even though a high *r*-value cannot be attained for a steel sheet with a high carbon content, a

Table 3 Tensile properties of STKM 15A (JIS 12A, 3.2 mm thickness)

	YS (MPa)	TS (MPa)	uEl (%)	total El (%)	*r*
HISTORY tube	532	638	17.9	30.9	1.52
Conventional ERW steel tube	515	614	13.7	26.9	0.89

YS: Yielding stress, TS: Tensile strength, uEl: Uniform elongation, total El: Total elongation, *r*: Lankford value

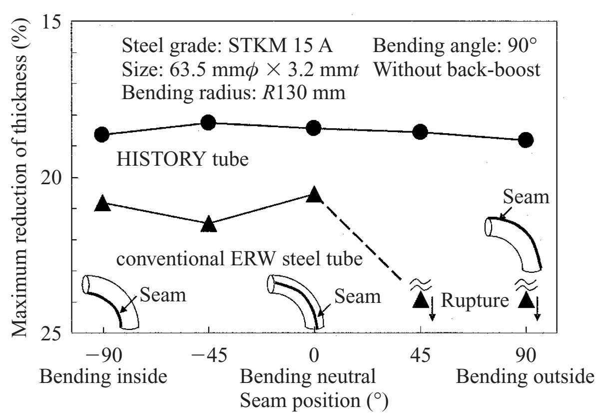


Fig.4 Maximum reduction of thickness in stretch-bending test

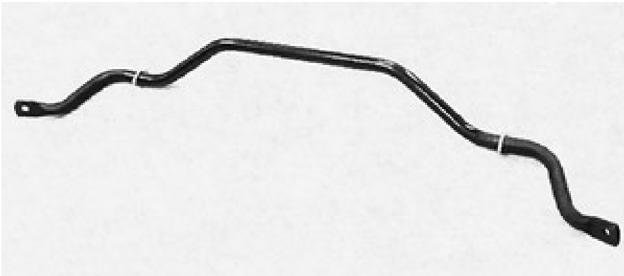


Photo 3 HISTORY tube application to automotive stabilizer

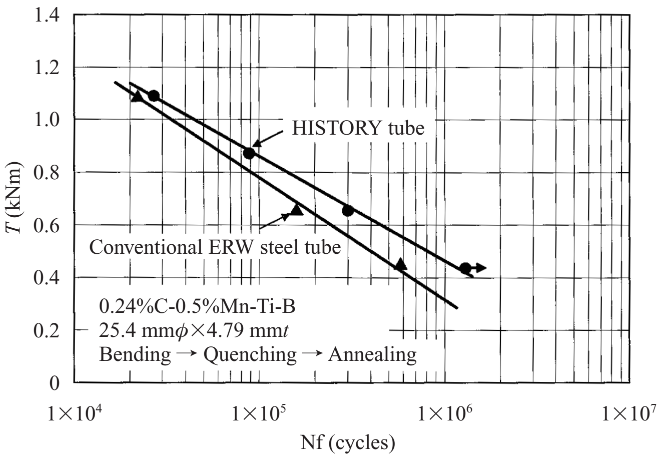


Fig. 5 Comparison of fatigue property between HISTORY tube and conventional ERW steel tube

high carbon steel tube attains a high *r*-value exceeding 1.5 by warm-reducing.

3.2 Applications of HISTORY Steel Tube

HISTORY steel tube has excellent characteristics as described above, and is a high carbon heavy gauge and small diameter steel tube suitable for automotive chassis parts such as stabilizers shown in **Photo 3**. According to a study of applying the tube to stabilizers, the fatigue life in actual parts shapes fabricated by HISTORY steel tube exhibits twice compared with conventional ERW steel tube, owing to the favorable bending formability and the high dimensional accuracy, as shown in **Fig. 5**.

4. Forming Technology of High Strength Steel Tube

Applications of steel tubes to automotive parts have drawn attention in recent years, and there are many reports on the applications of tube hydroforming (THF)[18]. Ordinary base materials used for THF are mainly 290 MPa class (JIS STKM 11A) to 440 MPa class (13B). The formability of automotive steel tubes having that level of strength is generally high, and there have been many studies on the expansion formability of mother tube[19]. On the other hand, high strength steel tubes exceeding the above class levels become less formable as the strength increases, so it is important to select adequate forming processes and conditions, taking into account the forming characteristics of the mother tube. For the formed parts, the performance characteristics of parts must be fully considered, taking into account the strength increase accompanied with the work-hardening, or the influence of wrinkles appearing during forming.

JFE Technical Report No. 4 outlined various working characteristics necessary in THF[1]. This section focuses on the bending technology which has been examined in only a few reports, though the technology is often applied to secondary tube-forming for automotive parts, and describes the bending characteristics and new bending technology for the high strength steel tube.

4.1 Bending Formability

Bending of steel tubes for automobiles is often conducted by rotary draw bending[20]. The rotary draw bending process (**Fig. 6**) is suitable for jobs involving relatively small bending radius because wrinkles can be prevented at the inner side of the bend using a wiper die, and the wall-thickness reduction at the outer side of the bend can be suppressed by using the back thrust of a tube booster in this process. Particularly when a high strength tube is bent to a small bending radius, the fracture caused by the wall-thickness reduction (especially, local necking) at the outer side of the bend must be prevented. Accordingly, it is important to assure ductility of the mother tube and to suppress wall-thickness reduction by optimizing the bending conditions.

Table 4 shows the mechanical properties of high strength steel tubes for the bending test, which have different strength levels and production histories from each other. The bending experiment was performed under a condition of $R/D = 2.05$, without thrust of the tube booster. The distribution of the wall-thickness at the inner side and outer side of the bend was investigated, and the result is shown in **Fig. 7**[21]. According to the rotary draw bending of 500 MPa class steel tubes, only the as-roll-formed ERW steel tube (base material A) suffered a local necking during the initial period of bending, and no local necking occurred for the heat-treated

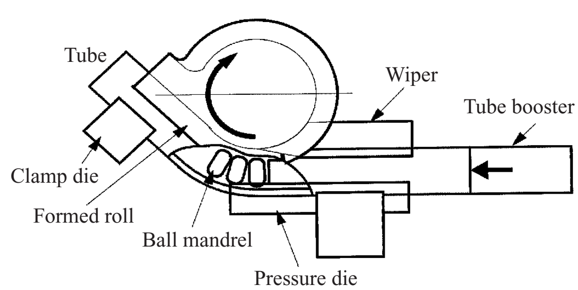
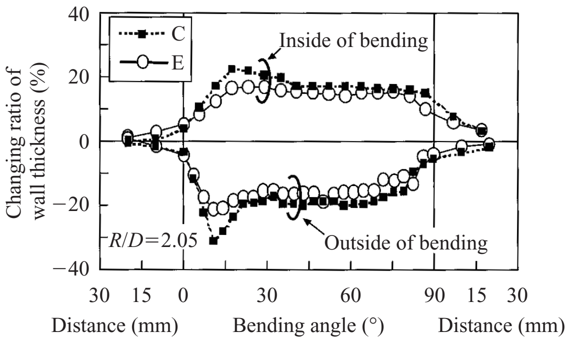


Fig. 6 Schematic illustration of tube rotary draw bending equipment

Table 4 Tensile properties of steel tubes for rotary draw bending (OD63.5 × t3.2 mm)

Pipes			YS (MPa)	TS (MPa)	El (%)	n-value (ε=5–15%)
ERW steel pipes	A	As rolled pipe	515	614	27	0.11
	B	Heat treated at 900°C	384	581	31	0.20
	C	Heat treated at 900°C	576	711	21	<0.10
HISTORY pipes	D	The same material as A and B	532	638	31	0.20
	E	The same material as C	565	796	25	<0.10

YS: Yielding stress, TS: Tensile strength, El: Elongation



Specimen E is TS780 MPa grade HISTORY tube, which is compared by that of conventional electric resistance welded steel pipe type C.

Fig. 7 Wall thickness distribution of high tensile steel tubes in rotary draw bending

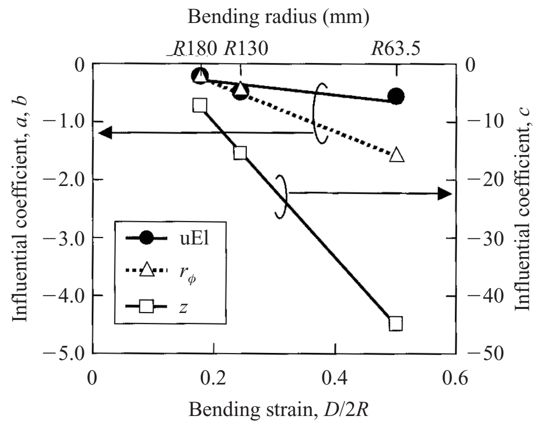


Fig. 8 Change of influential coefficients of the Eq. (1)

ERW steel tube (B) and the HISTORY steel tube (D). In further high strength regions, significant local necking occurred in the heat-treated ERW steel tube (C), though very little local necking occurred in the 780 MPa class HISTORY steel tube (E).

There are a few reports[22] on the influence of mechanical properties of mother tube on the wall-thickness reduction, and no reports on the matter relating to high strength steel tubes. To investigate the influence of mechanical properties and working conditions on the maximum wall-thickness reduction rate during rotary draw bending, the experimental results of the rotary draw bending for 370–780 MPa class steel tubes were applied to the statistical analysis. The applied mechanical properties were uniform elongation (uEl) and the r-value in the longitudinal direction of the tube (r_ϕ). The applied bending condition was the back boost pressure ratio induced by the tube booster (z = Pb/YS, Pb = (thrust of tube booster)/(cross sectional area of mother tube). **Figure 8** shows the observed variations of individual influential coefficients in Eq. (1) relating to the maximum wall-thickness reduction rate γ on the bending radius. A smaller bending radius gives a stronger effect of the n-value and r-value of the base material on the suppression of wall-thickness reduction[21]. Consequently, for smaller bending radius, it becomes increasingly important to improve the mechanical properties in order to suppress the wall-thickness reduction.

$$\gamma = a \cdot \mathrm{uEl} + B \cdot r_\phi + c \cdot z + d \quad \cdots\cdots (1)$$

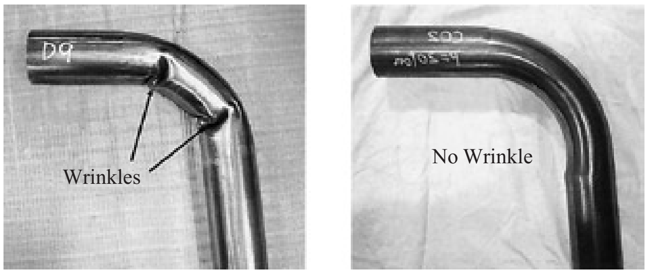
4.2 New Bending Technology

The application of a wiper die and ball type mandrel is essential for bending tubes of thin wall thickness by using the rotary draw bending technology and it makes difficult to shorten the manufacturing time. Furthermore, the higher strength tubes require the stricter adjustments of the tools and the bending conditions.

JFE Steel, jointly with Toyota Motor Corp. and Taiyo Corp., developed a bending technology to bend a high strength steel tube to a relatively small bending radius without using a wiper or mandrel in order to improve the technological problem in the rotary draw bending, and developed a new bending technology applying the reducing technology. On bending a 780 MPa class ERW steel tube (R/D = 2.0) without applying a wiper die and mandrel (**Photo 4**), the developed bending method gave a good bending shape with less reduction in wall-thickness, though the rotary draw bending method generated large wrinkles at the inner side of the bend.

4.3 Effect Extending to THF Technology

New automotive parts using high strength steel tubes have been commercialized, by applying the above-described bending characteristics and new bending method. When applying the THF process to the forming



(a) Rotary draw bending (b) New bending method

Photo 4 Shapes of bent tubes (Tube size: ϕ70 × t2.6 mm, 780 MPa grade ERW steel tube)

of three-dimensional parts with complex cross sectional shapes, the bending technology in the preliminary forming stage is particularly important.

5. Conclusion

JFE Steel has developed high performance steel tubes, and flexibly combined the secondary tube-forming technology such as bending of steel tube and the performance evaluation technology, thereby developing various products of many automotive steel tubes. JFE Steel will continue to develop new steel tubes for automotive parts to meet the requirements for further weight reductions and stronger car bodies.

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