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Development of High-Strength Martensitic Stainless Steel YUS 550 for Architectural Use

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Abstract:

Recently, higher corrosion resistance is necessary for self-drilling and -tapping screws. Conventional high-strength stainless steel wire rods do not have all of the mechanical properties, corrosion resistance, and manufacturability required of self-drilling and -tapping screws, prompting the demand for the development of new stainless steels for this application. Martensitic stainless steels can be improved in hardness and corrosion resistance by keeping the carbon content, nitrogen content, and anti-rusting index (ARI = Cr + 2.4Mo) of suitable levels and preventing the formation of δ-ferrite. A new martensitic stainless steel, designated YUS 550 and designed with an optimum composition (13% Cr, 1.5/2.4% Ni, 2% Mo, 0.16% C, 0.1% N and 0.003% B), has been developed for self-drilling and -tapping screws. Integrated manufacturing conditions have also been established for YUS 550.

1. Introduction

In recent years, stainless steels and coated steels have come to be widely used in buildings and automobiles, among other things, because of their corrosion resistance. These sheet products are generally spot welded, screwed, or nailed to the surface of structures. In view of its ease of use, screwing is a popular method for fixing steel sheets to structures built of steel shapes, for example. A conventional method for fastening an exterior decorative steel sheet to a steel structure consisted of drilling pilot holes in the exterior steel sheet and the steel structure, aligning the pilot holes, and driving a screw through the aligned pilot holes to fix the exterior decorative steel sheet to the steel structure, as illustrated in **Fig. 1**(a).

Recently, another method has been put into practice. A special screw, called the self-drilling and -tapping screw, is driven directly into the exterior decorative steel sheet without drilling a pilot hole, as shown in **Fig. 1**(b). The tip of the screw is machined into the tip of a drill and driven into the exterior decorative steel sheet and support steel structure. At the same time, the screw taps the exterior steel sheet and support steel structure. This fastening method is studied for use in steel-framed houses and other applications. The self-drilling and -tapping screw is

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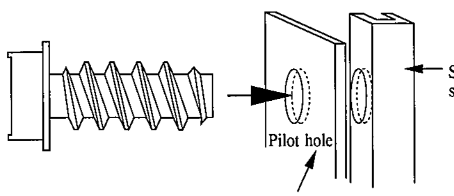

Fig. 1 (a)Fastening method with machine screw

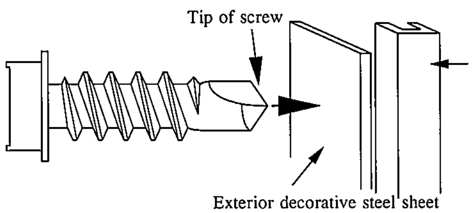

Fig. 1 (b)Fastening method with self-drilling and -tapping screw

made entirely of high-carbon steel strengthened by quenching, or the tip alone is made of tool steel or other high-strength steel and is joined to the body of the self-drilling and -tapping screw.

In recent years, the corrosion of self-drilling and -tapping screw joints has caused rust seepage and in-service corrosion resistance deterioration, and the insufficient corrosion resistance of the high-carbon steel and tool steel has become apparent. This situation has led to rising demand for steels with higher corrosion resistance for use as materials for the self-drilling and -tapping screws. Especially in Europe where acid rain is a serious environmental issue, self-drilling and -tapping screws made of stainless steel with high corrosion resistance are in strong demand.

This paper describes the development of a new martensitic stainless steel, designated YUS 550, for high-strength, high-corrosion resistance, self-drilling and -tapping screws and the applicability of YUS 550 to pins and other high-strength fasteners.

2. Guidelines for Development of Martensitic Stainless Steel YUS 550 for High-Strength, High-Corrosion Resistance, Self-Drilling and -Tapping Screws

2.1 Necessary properties of self-drilling and -tapping screws and performance of conventional self-drilling and -tapping screws

The necessary properties of stainless steel self-drilling and -tapping screws are listed in **Table 1**. The product properties include drivability and corrosion resistance. The manufacturing properties include cold workability and tool life. These four properties are described below.

1) Drivability

To fasten exterior decorative steel sheets to existing steel channels or the like, the self-drilling and -tapping screws must be drivable into steel sheets at least 5.5-mm thick to ensure their versatility. The relationship between tip hardness and drivable steel sheet thickness is shown in **Fig. 2**. The minimum tip hardness required to drive a screw into a 5.5-mm thick steel sheet is 500 Hv.

Table 1 Properties required of self-drilling and -tapping screws

Property	Target
Hardness (drivability)	Tip hardness ≥ 500 Hv (screw drivable through 5.5-mm thick steel sheet)
Corrosion resistance	As corrosion resistant as SUS 340 [No corrosion in salt spray test (5% NaCl, 350°C, 240 h)]
Cold workability	As work hardenable as SUS 304
Tool life	No damage to tools used to make 5,000 screws

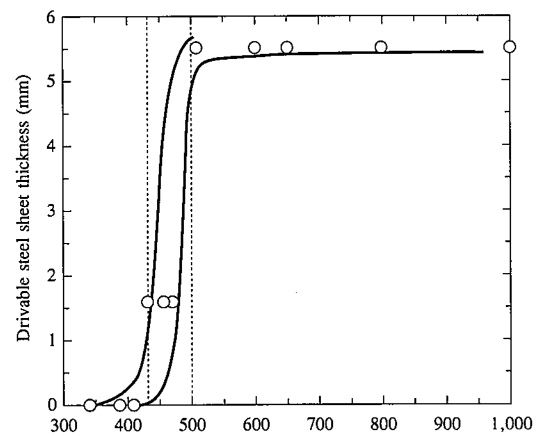

Fig. 2 Relationship between tip hardness and drivability

2) Corrosion resistance

Because the screw head is exposed on the surface of the coated or stainless steel sheet, its corrosion resistance must equal or exceed that of the steel sheet (SUS 304 for general-purpose service) and must not corrode in the salt spray test (5% NaCl, 35°C, 240 hours).

3) Cold workability

The screw material must have work hardening characteristics comparable to those of SUS 304 so that it can be easily worked into screws.

4) Tool life

Tool life as long as that of conventional cold-working tools is required. Given actual productivity, tools must not be damaged when used to produce more than 5,000 screws.

Conventional self-drilling and -tapping screws were tested to see if they could meet these product performance requirements, especially drivability and corrosion resistance. In accordance with Japanese Industrial Standards (JIS) B 1125, screws were driven into a 5.5-mm thick steel sheet and examined. Screws were marked ○ if driven successfully through a 5.5-mm thick steel sheet and × if not. For hardness evaluation, each screw was longitudinally cut. On screws without a surface hardened layer, the hardness at 0.1 mm below the tip of the screw was measured with a Vickers microhardness tester. If there was a surface hardened layer, it was measured. For corrosion resistance evaluation, each screw was inserted into foamed styrene at a 20° angle, salt spray tested in a 5% NaCl solution at 35°C for 240 hours, and examined for head corrosion. Screws were marked ○ if their heads were not corroded and × if they were.

Table 2 gives the performance evaluation results. The conventional self-drilling and -tapping screws can be classified by strengthening method into the following four groups:

1)After the screw is formed of SUS 340 and surface hardened by nitriding[1,2], its tip hardness is 1,000 Hv, and its drivability is good. The nitriding treatment causes red rust throughout the screw.

2)After the screw is formed and strengthened by quenching, its tip hardness ranges from 600 Hv to 650 Hv, and its drivability is good. The screw is treated against corrosion, but it develops white and red rust throughout.

3)After the screw is work hardened during forming and age hardened later, its tip hardness ranges from 470 Hv to 490 Hv, and its drivability is poor. The screw is coated with zinc for surface lubrication and has white rust throughout.

4)After high-hardness carbon steel tip is joined to an SUS 340 screw head, its tip hardness is about 650 Hv, and its drivability is good. The screw is coated with zinc and develops white rust on the entire head surface.

The above results confirmed that the conventional self-drilling and -tapping screws made of stainless steel such as SUS 340 and surface hardened have excellent drivability but poor corrosion resistance.

2.2 Property evaluation of conventional high-strength stainless steels

To clarify development guidelines, sample self-drilling and -tapping screws were made from conventional high-strength stainless steel wire rods and evaluated for suitability, including manufacturability.

2.2.1 Experimental materials and trial manufacture and evaluation methods

Before trial manufacture, the performance of conventional high-strength stainless steels was arranged in terms of 1) hardness, 2) corrosion resistance, 3) cold workability, and 4) tool life.

Table 3 lists the chemical compositions of candidate high-strength stainless steels. Austenitic, martensitic, and precipitation-hardening grades are included.

The hardness of specimens hardened after cold working was measured. From **Fig. 3**, it is evident that when cold worked and aged, SUS 631J1 and YUS 130M can meet the minimum target hardness of 500 Hv.

The corrosion resistance of the steels can be properly evaluated by the anti-rusting index (ARI). **Fig. 4** shows the relationship between the ARI (= Cr + 2.4Mo) and the pitting potential[3]. The pitting potential increases with increasing ARI. The target corrosion resistance (equal or superior to the corrosion resistance of SUS 304) can be achieved by selecting a stainless steel with ARI ≥ 18.

Cold workability and tool life were evaluated by the work hardening characteristics of wire rods before forming into screws. **Fig. 5** shows the work hardening curves of conventional stainless steels. Among the conventional stainless steels, SUS 305 and SUS 410 have low work hardening characteristics and are thus considered to assure good cold workability and tool life.

The above results suggest that YUS 130M, SUS 305, and SUS 410 are promising materials for self-driving and -tapping screws. It was thus decided to make samples of self-drilling and -tapping screws from wire rods of these steels.

Rods were drawn and intermediately annealed to specified sizes of wire and then cold formed into self-drilling and -tapping screws. The SUS 305 screws were surface hardened to ensure drivability, the SUS 410 screws were quenched from 1,000°C, and the YUS 130M screws were aged at 500°C. Sample screws with joined tips were not made because a special manufacturing process was thought to be necessary.

The evaluation items were drivability, corrosion resistance, cold workability, and tool life. Drivability and corrosion resistance were evaluated by the same methods as used for the conventional self-drilling and -tapping screws. Cold workability was evaluated according to whether or not the screws cracked as they were formed. A self-drilling and -tapping screw is marked ○ if it did not crack during the forming operation and × if it did. Tool life was evaluated according to whether or not the tools were damaged when used to form 5,000 screws.

Table 2 Performance of self-drilling and -tapping screws

Method of strengthening	Type of steel	Treatment of screw after forming	Tip hardness Hv	Drivability	Corrosion resistance
Surface hardening	SUS 304	Nitriding+aluminum or zinc coating	1,000	○	×
Quenching	Carbon steel	Carbonitriding quench+zinc coating	650	○	×
	SUS 410	Nitriding quench+tempering	600	○	×
Work and age hardening	SUS 304	Aging+zinc coating	470-490	×	×
Joining	SUS 304	Carbon steel tip joining+zinc coating	650	○	×

Table 3 Chemical compositions of typical conventional stainless steels

Type	Steel	Chemical composition (mass%)					
		C	Mn	Ni	Cr	N	Balance
Austenitic	SUS 304	0.04	1.2	9.1	18.2	0.02	
	SUS 304N	0.05	1.1	8.1	18.2	0.20	
	SUS 305	0.03	1.1	10.3	18.3	0.04	
	YUS 130M	0.09	9.0	9.5	18.0	0.30	
Martensitic	SUS 410	0.10	0.6	0.2	11.6	0.01	
Precipitation hardening	SUS 630	0.03	0.5	4.7	16.4	0.01	3.5Cu-0.3Nb
	SUS 631J1	0.07	0.7	7.2	16.5	0.02	1.0A1

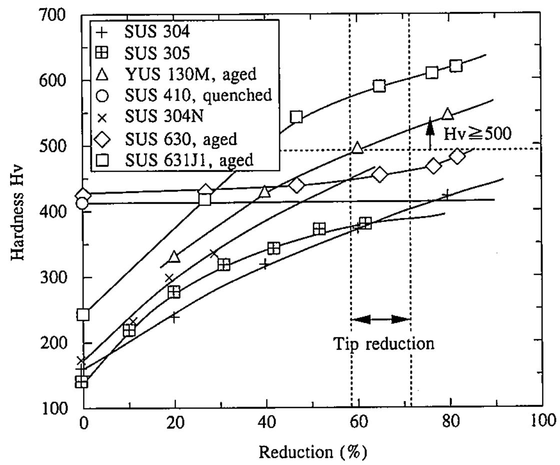

Fig. 3 Relationship between reduction and hardness of screws made of conventional stainless steel, cold worked, and hardened by heat treatment

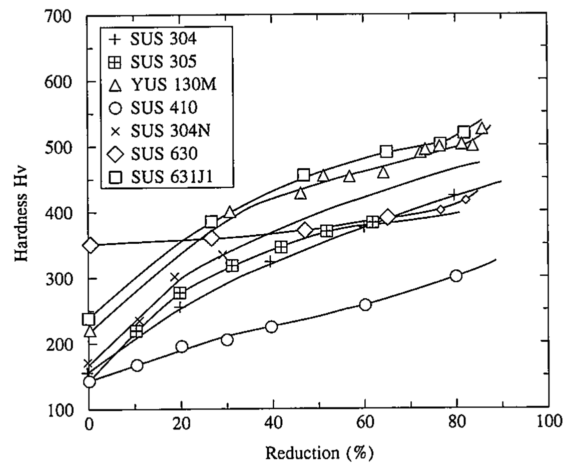

Fig. 5 Work hardening curves of wires

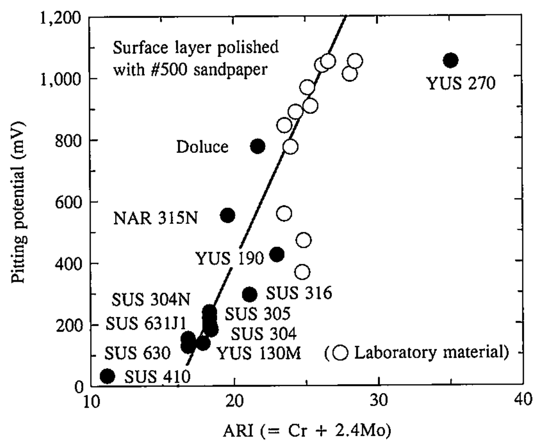

Fig. 4 Relationship between ARI and corrosion resistance

2.2.2 Evaluation results

The evaluation results are summarized in **Table 4**. If not surface hardened or coated, the SUS 305 screws have excellent corrosion resistance, workability, and tool life, but low tip hardness at 380 Hv to 400 Hv and poor drivability.

If surface hardened, the SUS 305 screws have high tip hardness at about 1,000 Hv and superior drivability. Formation of a nitrided surface layer, however, impairs their corrosion resistance. The relationship between the hard surface layer thickness and the drivable steel sheet thickness is shown in **Fig. 6**. The drivable steel sheet thickness increases with increasing hard surface layer thickness. The hard surface layer thickness required for a 5.5-mm thick steel sheet is about 60 μm or more. A uniform hard surface layer of about 60 μm minimum thickness calls for a special process[3] and is difficult to obtain on an industrial basis.

The SUS 410 screws have good cold workability and tool life, but low tip hardness at 420 Hv and poor drivability. They also develop red rust throughout and have low corrosion resistance.

The YUS 130M screws excel in corrosion resistance and cold workability, but greatly vary in tip hardness from 460 Hv to 550 Hv and have low drivability. Their large work hardening degree also shortens the tool life.

The above results show that self-drilling and -tapping screws made of conventional stainless steel wire rods do not meet all of the property requirements.

2.3 Development guidelines

The conventional stainless steel wire rods were found to be difficult to apply to self-drilling and -tapping screws in terms of performance or manufacturability, which indicated the need for developing new stainless steel wire rods.

To summarize development issues with the conventional stainless steels, the austenitic stainless steels SUS 305 and YUS 130M must be hardened by heat treatment when their hardness is low in

Table 4 Performance of sample self-drilling and -tapping screws made from conventional stainless steels

Method of strengthening	Type of steel	Treatment of as-formed screw	Tip hardness Hv	Drivability	Corrosion resistance	Cold workability	Tool life
Surface hardening	SUS 305	None	380-400	×	○	○	○
		Tufftriding*1	1,000	○	×	○	○
		Tufftriding + Dacromet*2	1,000	○	×	○	○
Quenching	SUS 410	1,000°C quenching + tempering	420	×	×	○	○
Work and age hardening	YUS 130M	Aging (500°C)	470-550	×	○	○	×

*1: Nitriding for surface hardening by immersion in slat bath at about 550°C

*2: Coating with Al-Zn-Cr alloy for corrosion resistance

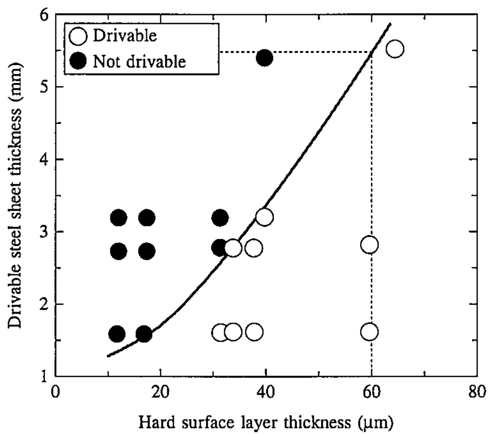

Fig. 6 Relationship between thickness of hard surface layer (≧ 1,000 Hv) of surface-hardened screws (matrix hardness = 350-400 Hv) and drivable steel sheet thickness

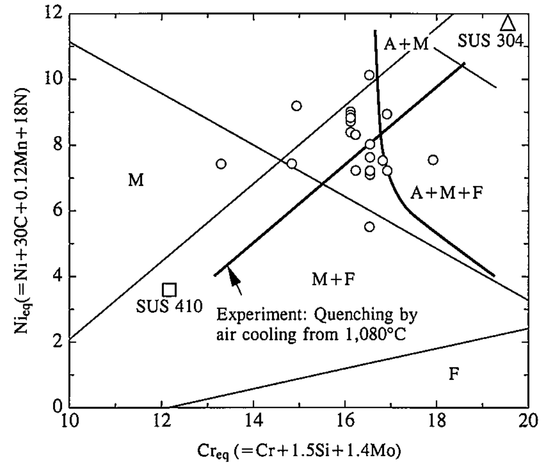

Fig. 7 Microstrutural ranges of matrix solidification structure and 1,080°C×30 minutes air-cooled region

the screw stage in order to improve workability and tool life. Increasing strength and corrosion resistance by surface coating or joining calls for a complicated manufacturing process. The martensitic stainless steel SUS 410 work hardens less than the austenitic stainless steels SUS 305 and YUS 130M. SUS 410 has satisfactory screw formability and tool life, but its hardness and corrosion resistance must be improved.

Because the manufacturing process of the austenitic stainless steels is complicated by the need for hardening as noted above, the target properties are considered to be achievable with a new martensitic stainless steel. In other words, the targets of hardness and corrosion resistance can be met by controlling the carbon content, nitrogen content, and ARI of a conventional martensitic stainless steel.

A martensitic composition was thus selected as the base composition for developing a new stainless steel for self-drilling and -tapping screws.

3. Development of High-Strength, High-Corrosion Resistance Martensitic Stainless Steel YUS 550

The alloy design of a high-strength, high-corrosion resistance martensitic stainless steel for self-drilling and -tapping screws was determined to improve hardness and corrosion resistance as discussed above.

3.1 Experimental methods

Samples of the chemical compositions listed in **Table 5** were selected to investigate the effects of carbon, nickel, chromium, molybdenum, boron, and nitrogen on the hardness, corrosion resistance, toughness, and hot workability of martensitic stainless steels.

Table 5 Chemical compositions of high-strength martensitic stainless steel samples (mass%)

C	Si	Mn	Ni	Cr	Mo	B	N
0.05			1.7	13.0	0	0	0.01
~	0.2	0.3	~	~	~	~	~
0.2			2.4	16.2	2.5	0.006	0.12

The samples are practically close to the martensite phase in chemistry. Their solidification structures are shown on the phase diagram of Markus[4] in **Fig. 7**.

Each sample was melted in a 45-kg vacuum melting furnace, hot extruded to a 16-mm diameter bar, quenched by air cooling from 1,000°C to 1,250°C at a rate of about 5°C/s, and tempered at 0°C to 200°C. The samples had such good hardenability that they cracked when quenched by water cooling. Because of this, they were quenched by air cooling. Their microstructure, hardness, and corrosion resistance were then evaluated. Each specimen was etched with aqua regia and observed under an optical microscope. Hardness was measured with a Vickers microhardness tester, and corrosion resistance was evaluated by the occurrence of corrosion and the pitting potential measured in the salt spray test (5% NaCl, 35°C, 240 hours). To evaluate product toughness, specimens measuring 10 mm × 10 mm × 55 mm and machined with a 2-mm wide and 1-mm deep U-notch were taken and Charpy impact tested. Hot tension test specimens, measuring 8 mm in diameter and 110 mm long, were machined from some billets and tested for hot workability (rod rollability).

3.2 Experimental results and discussion

The microstructures of the samples after quenching at 1,080°C for 30 minutes are shown in **Fig. 7**. Delta-ferrite was determined by the image analysis of optical microstructures, and retained austenite was measured by X-ray diffraction. Heat treatment expanded the martensite region.

The effect of the combined carbon and nitrogen content on the hardness of samples quenched from 1,150°C are shown in **Fig. 8**. When the combined carbon and nitrogen content is a maximum of about 0.27%, the hardness increases with increasing combined carbon and nitrogen content. The hardness peaks at about 600 Hv when the combined carbon and nitrogen content is about 0.27%. When this content exceeds about 0.27%, the hardness declines because of the formation of retained austenite. **Fig. 8** also shows that carbon is about 2.5 times more effective than nitrogen on hardness. The effects of carbon and nitrogen on the optical microstructure of martensite are shown in **Photo 1**. Nitrogen has a greater effect than carbon on the grain refinement of the block structure that is the substructure of martensite. The difference in contribution to hardness between carbon and nitrogen arises from the difference in their effect on the block structure[5]. The formation of lenticular martensite is thought to have an effect on the grain refinement of the block structure.

The above results show that 2.5C + N must be set at a minimum of about 0.28% to achieve the minimum hardness target of 500 Hv.

The effects of the anti-rusting index (ARI = Cr + 2.4Mo) and δ-ferrite on the pitting potential are shown in **Fig. 9**. When δ-ferrite is not present, the pitting potential increases with increasing ARI. When the ARI is 18 or more, the martensitic stainless steels have corrosion resistance comparable to that of SUS 304. When δ-ferrite is present, the pitting potential drops. The salt spray test results show that the corrosion resistance improves with increasing ARI in the same way as with pitting potential but worsens in the presence of δ-ferrite. The diffusion rate of chromium in δ-ferrite is higher than in austenite. In a

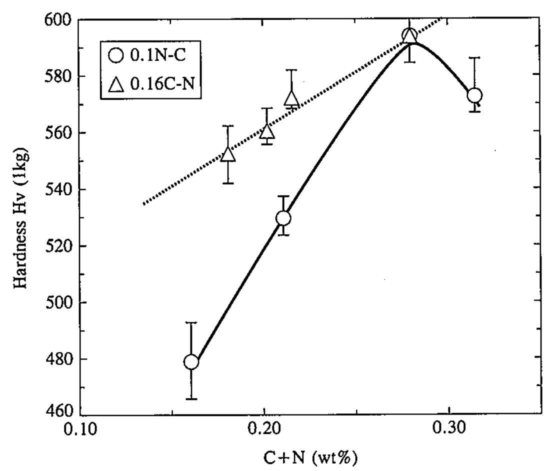

Fig. 8 Effect of combined carbon and nitrogen content on hardness of quenched specimens

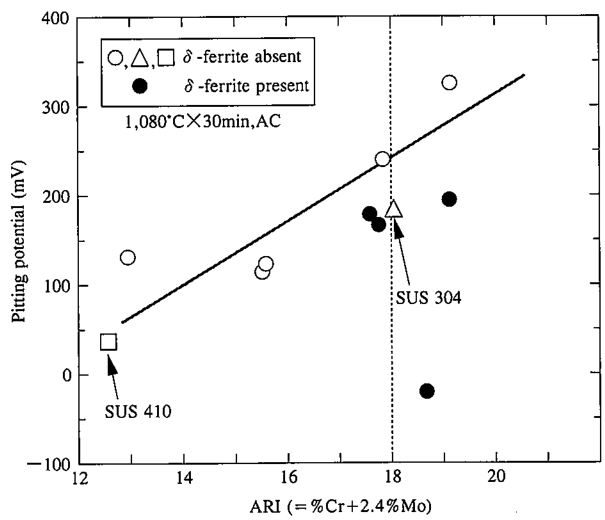

Fig. 9 Effects of ARI and δ-ferrite on pitting potential

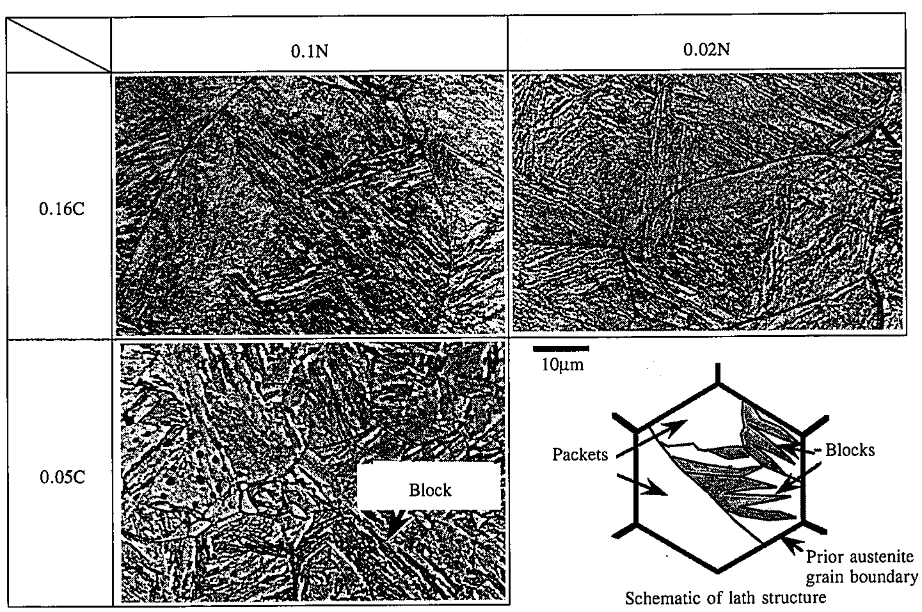

Photo 1 Effects of carbon and nitrogen on optical microstructure of martensite

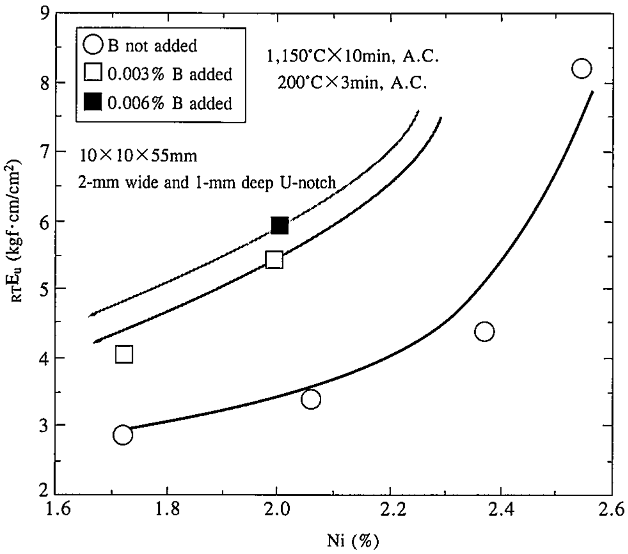

Fig. 10 Effects of nickel and boron contents on toughness

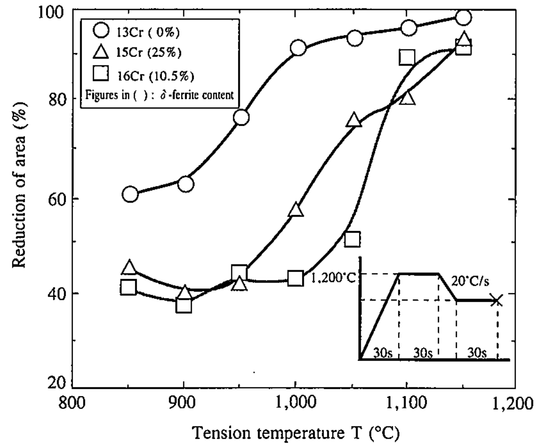

Fig. 11 Effect of chromium on reduction of area in hot tension test

steel that contains about 20% chromium, a δ-ferrite content of about a few percent relaxes the chromium-depleted zone and improves the corrosion resistance of the steel, despite the precipitation of chromium carbides at the grain boundaries[6].

With the low-chromium, high-carbon steels studied here, however, their corrosion resistance is markedly decreased by a few percent of δ-ferrite. Chromium carbonitrides precipitate in large amounts at the δ-ferrite interface in this type of steel, thus forming chromium-depleted zones of low chromium content in large amounts[7].

The effects of nickel[8] and boron on toughness are shown in **Fig. 10**. The toughness improves with increasing nickel content and improves further with the addition of boron. Fasteners are likely to have heads broken in cold regions when low-temperature toughness is not sufficient, for example. To provide a desirable level of toughness for self-drilling and -tapping screws, it is important to add nickel or boron, depending on the particular environment.

The effect of the δ-ferrite content after quenching at 1,080°C for 30 minutes on the reduction of area in the hot tension test is shown in **Fig. 11**. The reduction of area is one index of wire rod rollability. The reduction of area at which wire rods can be rolled without hot cracking is a minimum of 60% at or above 900°C. The reduction of area steeply decreases with increasing δ-ferrite content, which means that the formation of δ-ferrite must be prevented to achieve the target properties.

The above results indicated the needs for preventing the formation of δ-ferrite, assuring ARI ≥ 18 and 2.5C + N ≥ 0.28%, and for adding nickel and boron, in order to accomplish the target hardness ≤ 500 Hv, corrosion resistance comparable to that of SUS 304, high toughness, and good wire rod rollability. Accordingly, 13%Cr, 1.5/2.4% Ni, 2% Mo, 0.16% C, 0.1% N, and 0.003% B were designed as an optimum chemical composition to meet all of these property requirements.

4. Study of Commercial Manufacturing Conditions for YUS 550

An alloy of the design composition was commercially produced, and its manufacturing conditions were optimized to optimize product properties. Main issues with this chemistry are (1) selection of softening conditions before screw formation and (2) selection of product heat treating conditions to obtain optimum product properties. Softening conditions before screw formation and product heat treating conditions were studied as shown in **Fig. 12**. Product properties were also evaluated.

4.1 Study of softening conditions

To cold work a steel of this chemical composition into fasteners, the maximum hardness must be less than 300 Hv. Because the new martensitic stainless steel YUS 550 contains nickel, an element that increases hardenability and lowers the A_{c1} transformation temperature, YUS 550 becomes increasingly difficult to soften by annealing as the nickel content increases. The continuous cooling transformation (CCT) diagram of the 0.15C-2.4Ni-13Cr-2Mo-0.1N grade having the highest nickel content and greatest difficulty in softening among the grades of the steel with the designed chemical composition is shown in **Fig. 13**. When cooled at a very slow rate of 0.05°C/s, the 2.4% Ni grade passes through the martensite start and finish temperatures M_s and M_f, respectively, exhibits a minimum hardness of 500 Hv, and is

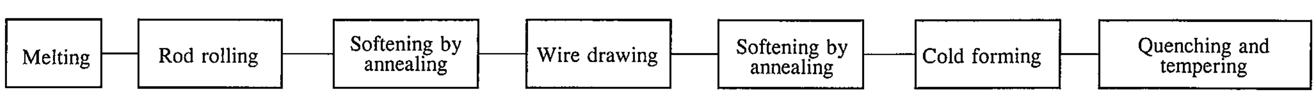

Fig. 12 Process for manufacturing self-drilling and -tapping screws from high-strength, high-corrosion resistance martensitic stainless steel YUS 550

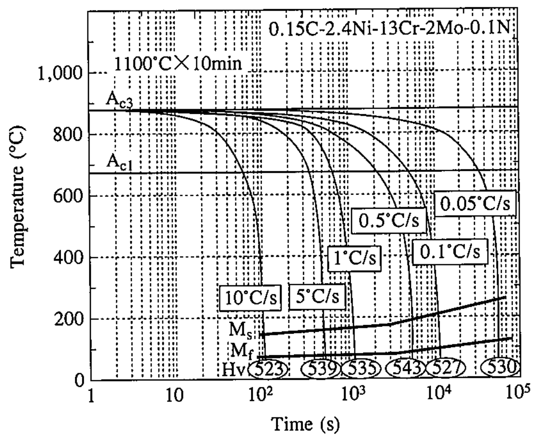

Fig. 13 Continuous cooling transformation (CCT) diagram of YUS 550 (2.4% Ni)

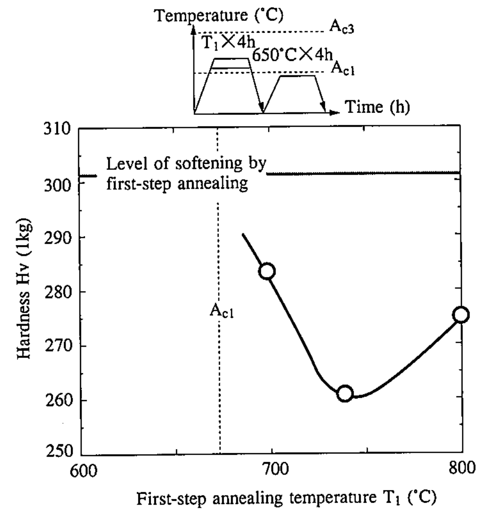

Fig. 15 Effect of first-step annealing temperature on hardness after two-step annealing

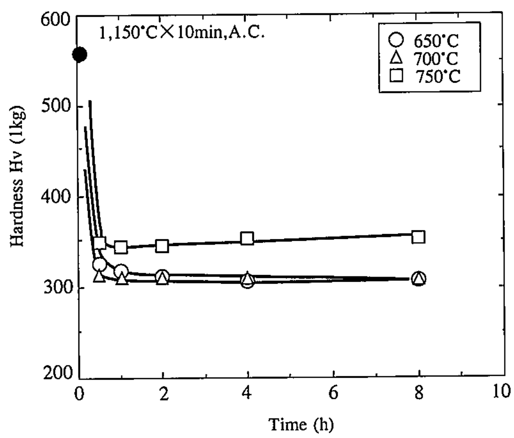

Fig. 14 Effect of annealing time on hardness after annealing

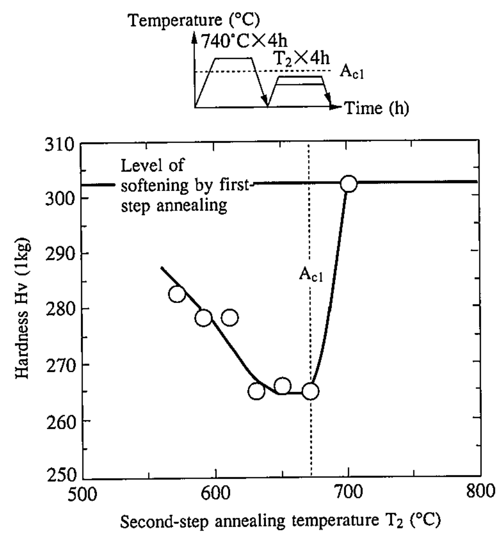

Fig. 16 Effect of second-step annealing temperature on hardness after two-step annealing

almost completely hardened. This means that softening by full annealing or isothermal annealing[9] on an industrial basis cannot be expected for the new martensitic stainless steel YUS 550.

The relationship between the hardness and annealing time of the steel when annealed around the A_{c1} transformation temperature of 670°C is shown in **Fig. 14**. Tempering at 650°C and 700°C softens the steel to about 300 Hv in one to two hours. Because this softening tendency is almost saturated in one to two hours, however, the target hardness of less than 300 Hv cannot be achieved. Two-step annealing at temperatures around the A_{c1} temperature was then studied. The two-step annealing heat pattern and the subsequent effect of the second-step annealing temperature on the hardness of the steel are shown in **Fig. 15**. The second-step annealing temperature was 650°C, or just below the A_{c1} temperature. Two-step annealing reduces the hardness to a level below than obtainable with low-temperature annealing, and a minimum hardness of about 260 Hv is obtained when the first-step annealing temperature is 740°C.

The effect of the second-step annealing temperature on the hardness of the steel after two-step annealing is shown in **Fig. 16**. When the steel is annealed at 740°C in the first step, it is most greatly softened to a hardness of about 260 Hv in the second-step annealing temperature range of 630°C to 670°C, or just below the Ac_1 temperature. A second-step annealing temperature of 610°C or less is low enough to inhibit the recovery of dislocations. A second-step annealing temperature of 700°C or more exceeds the Ac_1 transformation temperature, rehardens the steel with the development of some reverted austenite, and does not promote the softening of the steel.

The promotion of softening by two-step annealing may be explained as follows. Raising the temperature once above A_{c1} spheroidizes carbides and precipitates low-carbon and low-nitrogen austenite reverted from the vicinity of prior austenite grain

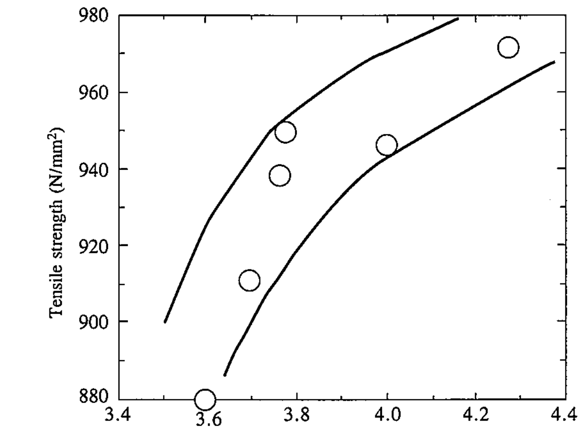

Fig. 17 Relationship between amount of extraction residue and tensile strength after two-step annealing

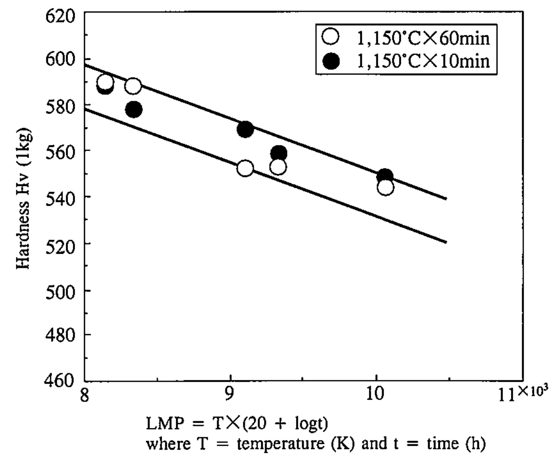

Fig. 19 Relationship between Larson-Miller parameter (LMP) and hardness

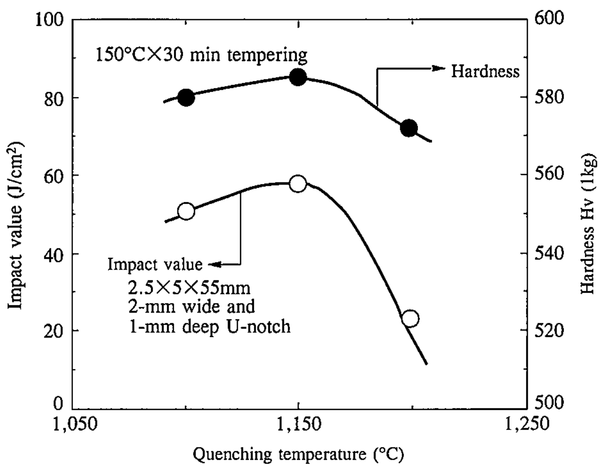

Fig. 18 Effect of quenching temperature on hardness and toughness

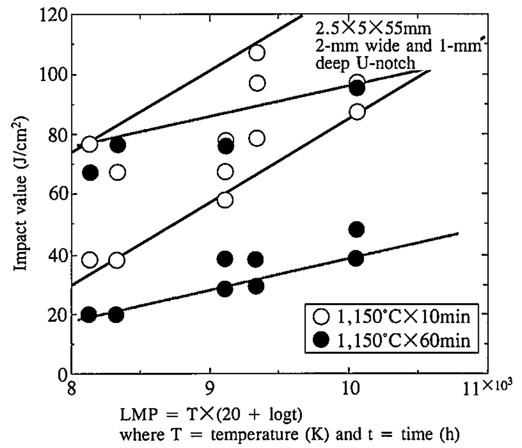

Fig. 20 Relationship between Larson-Miller parameter (LMP) and impact value

boundaries. The resultant destruction of the lath structure reduces the amount of rodlike carbides that are precipitated between the laths and that resist softening during tempering[10,11].

The variability of strength after two-step annealing is discussed next. **Fig.** 17 shows the relationship between the amount of extraction residue and the tensile strength of the steel by time of tapping. Grades of the same main composition actually vary in tensile strength and the amount of extraction residue after two-step annealing. The strength increases as the amount of extraction residue or precipitation increases. This variation in the amount of precipitation is attributed to the trace elements, such as aluminum and silicon, that affect the activity of carbon and nitrogen. That is, the trace elements are thought to change the activity of carbon and nitrogen and hence the amount of carbonitride formation. From this viewpoint, controlling the trace elements is important in fully promoting the softening of the steel.

As a result of what has been discussed above, the hardness of the new martensitic stainless steel YUS 550 before it is worked into a product can be controlled at about 260 Hv to 300 Hv, and simple screws and pins can be formed without damage to the tools used.

4.2 Study of product heat treating conditions

After screws are cold formed, they are quenched and tempered to impart necessary product properties. It is necessary to select optimum heat treating conditions for this purpose. **Fig.** 18 shows the effect of the quenching temperature on the hardness and toughness of screws quenched at different temperatures and tempered at 150°C. Quenching from 1,150°C provides a hardness of about 580 Hv and offers the highest possible toughness. When the quenching temperature is too high, the grains are coarsened. When the quenching temperature is too low, undisolved precipitates remain, and the impact value drops.

For these reasons, each steel must be quenched at its optimum temperature. **Figs.** 19 and 20 show the effects of the holding time before quenching and the amount of tempering on the hardness and toughness of screws quenched from 1,150°C and tempered, respectively. The Larson-Miller parameter (LMP) is plotted along the horizontal axis as an index of the amount of temper-

Table 6 Corrosion resistance of self-drilling and -tapping screws made of YUS 550, SUS 304, and SUS 410

Steel	Corrosion after slat spray test (5% NaCl, 35°C, 240 h)	Corrosion after sulfurous acid gas corrosion test (20 cycles as described in DIN 50018-21)	Pitting potential (mV)
YUS 550	No corrosion	No corrosion	220
SUS 304	No corrosion	Black rust partly caused	190
SUS 410	Red rust partly caused	Black rust generally caused	40

ing. A large LMP value means that the amount of tempering is large. Regardless of the holding time before quenching, the hardness gradually decreases with the amount of tempering. For example, tempering at 200°C for 30 minutes provides a hardness of 550 Hv. The toughness improves with tempering. A screw quenched after holding for 60 minutes is lower in toughness than a screw quenched after holding for 10 minutes. This is because the longer holding time coarsens the grain size.

4.3 Evaluation of product properties

Table 6 shows the corrosion and pitting potential of screw products quenched from 1,150°C, tempered at 200°C, salt spray tested in a 5% NaCl solution at 35°C for 240 hours, and sulfurous acid gas corrosion tested in 20 cycles as described in DIN 50018-21. SUS 410 develops red dust at a pitting potential of 40 mV, while YUS 550 is not corroded at a pitting potential of 220 mV and exhibits corrosion resistance comparable to that of SUS 304. YUS 550 is superior in sulfurous acid gas corrosion resistance to SUS 304 and is thought to show good corrosion resistance to acid rain. When a nitrogen-bearing steel is exposed to a weak acid, the dissolution of nickel helps the steel to exhibit excellent corrosion resistance to the weak acid[12]. YUS 550 also has a hardness of 550 Hv, and self-drilling screws of YUS 550 can be successfully driven through a 5.5-mm thick steel sheet.

To evaluate the corrosion resistance of self-drilling and -tapping screws in service, an ETCF coated steel sheet covered with a fluorine resin with good corrosion resistance was fastened to 5.5-mm thick steel channels with self-drilling and -tapping screws of YUS 550. The assembly was salt spray tested in the 5% NaCl solution at 35°C for 480 hours. Self-drilling and -tapping screws made from SUS 410 and a zinc-coated carbon steel were also tested as control materials. The corrosion of the fasteners after the salt spray test is shown in **Photo 2.** The steel sheet is not corroded. Red rust forms at the head of self-drilling and -tapping screws of SUS 410 and the carbon steel and runs down the steel sheet. The self-drilling and -tapping screw of YUS 550 has no corrosion produced at the head, exhibits good corrosion resistance, and does not impair the aesthetic appearance of the coated steel sheet.

The development project has succeeded in manufacturing self-drilling and -tapping screws with good corrosion resistance and drivability.

5. Conclusions

Materials for self-drilling and -tapping screws with high strength and corrosion resistance were studied. The following results were obtained:

(1)Conventional stainless steel wire rods are difficult to apply to self-drilling and -tapping screws with high strength and corrosion resistance in terms of performance or manufacturability. A modified martensitic stainless steel is promising for this application.

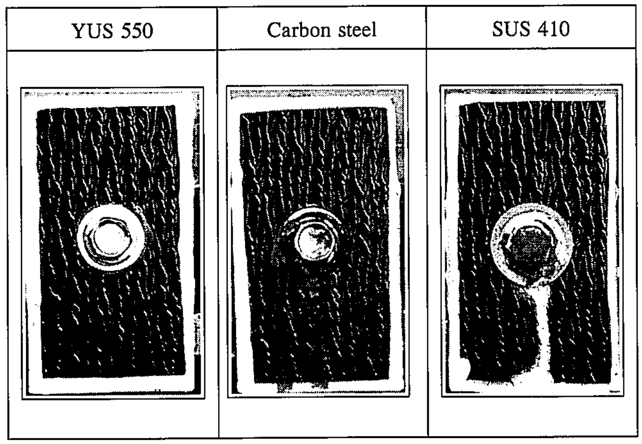

Photo 2 Corrosion of fasteners after salt spray test (5% NaCl, 35°C, 480 hours)

(2)A martensitic stainless steel can be provided with corrosion resistance comparable to that of SUS 304 by increasing the anti-rusting index (ARI = Cr + 2.4Mo) to 18 or more and preventing the formation of δ-ferrite.

(3)Carbon is about 2.5 times as effective as nitrogen on the hardness of martensitic stainless steels. A hardness of 500 Hv minimum is obtained when $2.5C + N \geq 0.28\%$.

(4)The addition of nickel and boron increases the toughness of martensitic stainless steels.

(5)A new steel, designated YUS 550 with the chemical composition 13Cr-1.5-2.4Ni-2Mo-0.16C-0.1N-0.003B, has been developed for self-drilling and -tapping screws with high strength and corrosion resistance.

(6)When YUS 550 is annealed first at a temperature above the Ac_1 transformation temperature and then below that temperature, YUS 550 assumes a hardness of about 260 Hv to 300 Hv and can be properly cold formed into screws.

(7)When screws formed from YUS 550 are quenched from 1,150°C and tempered at 200°C, they are provided with a hardness of about 550 Hv and can be successfully driven through a 5.5-mm thick steel sheet. When the screws are quenched at a higher temperature and held for a longer time, their toughness deteriorates owing to grain size coarsening.

At present, YUS 550 is used to fabricate not only self-drilling and -tapping screws, but also pins and other high-strength fasteners. Many other applications need to be found. YUS 550 is now softened to a hardness of about 260 Hv to 300 Hv and is not worked into complex shapes. For YUS 550 to be used in many new applications, it will be necessary to lower its strength before forming it into products and to assure desired cold workability.

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