Development of Steel Wires for Self-Drilling and Self-Tapping Screws in Japan

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Introduction on Self-Drilling and Self-Tapping Screws

In recent years, there has been a much wider range of applications in the fields of construction and automobile industries for stainless or plated sheet steels than any other sheet steels, and that is because of the feature of corrosion resistance. The products of such sheet steels are often mounted to surface of steel structure by processes of welding, fastening, or tapping. Due to the convenience of their usage, screws are commonly used to fix sheet steels to extruded steel structural framework. By the example of fixing exterior steel sheet to steel structural framework, the most common practice includes the following procedures: 1. Drill preset holes on sheet steels and steel structural framework, respectively, 2. Align the holes in order for screws to be inserted correctly to enable fixing of sheet steels to steel structural framework as illustrated in Figure 1. (a).

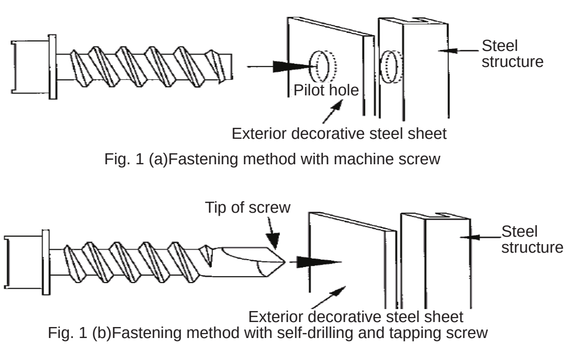


Figure 1. Fastening with Machine Screws vs. Self-Drilling and Self-Tapping Screws

Source: Nippon Steel Monthly, No. 361 (1996)

Around twenty years ago, there came available an application of a special type of self-drilling and self-tapping screws that were capable of penetrating through steel sheets without requiring the drilling of preset holes. The tip of this type of screws needed a process to form a chisel-like point with helical threads available to penetrate the steel sheet through when the screw was driven in as illustrated in Figure 1 (b). The body of this type of screws was made of high carbon steel wires that were quenched for hardening, and the tips were made of high-strength steel wires purposed for tooling. Two sections of the screw body and the head were mounted using surface mounting technology by electric resistance, but neither of these two types of steel wires have adequate amount of corrosion resistance; the surface mounted interface is very vulnerable to the attack of corrosive elements. Therefore, an innovative type of steel wire is urgently needed that can feature high corrosion resistance for the application of self-drilling and self-tapping screws. This demand is particularly high for users in Europe where the effect of acid rain is a great concern.

Evaluation on Features of Conventional Self-Drilling and Self-Tapping Screws

The features required of self-drilling and self-tapping screws by construction-related applications are shown in Table 1, including product-related features of penetration and corrosion resistance, and process-related features of cold forging workability and tool life. These features can be described below.

Table 1. Features Required of Self-Drilling and Self-tapping Screws

Feature	Requirements
Vickers Hardness (Penetration)	Tip hardness Hv≧500 (available to penetrate through 5.5mm thick steel sheet)
Corrosion Resistance	Equivalent to SUS304 (salt spray resistance at 5% NaCl, 35℃, 240h)
Cold Forging Workability	Hardening workability equivalent to or below SUS304
Tool Life	No sign of tool wear after tooling 5,000 screws

Source: Nippon Steel Monthly, No. 361 (1996)

Penetration

With the case of fixing exterior steel sheet to steel structural framework, to ensure general applicability, adequate tip hardness should be available to penetrate through 5.5mm thick steel sheet. The relation between tip hardness and thickness of drivable steel sheet is shown in Figure 2, which indicates that, in general, the hardness required for tips to penetrate through 5.5mm thick steel sheet is 500Hv or above.

Corrosion Resistance

Because screw heads are always exposed on the surface of stainless or plated sheet steels, screws are required to feature corrosion resistance that is equivalent to or above that of sheet steels (by general applications, equivalent to or above SUS304), or salt spray resistance at 5% NaCl, 35%, 240h without pitting or rust.

Cold Forging Workability

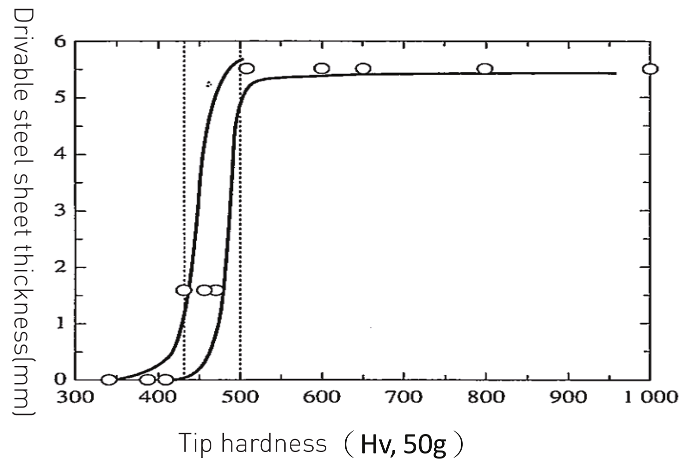
To facilitate easy work on products, the workability for processing cold forging hardening should be equivalent to or below type SUS304.

Tool Life

Ideally, tool life of the screws should be as long as that of cold forging work, but considering the practical situation in production, adequate tool life means tooling 5,000 screws without a sign of tool wear.

We then evaluated conventional self-drilling and self-tapping screws to see if these products meet the requirements of necessary features mentioned above, such as penetration, corrosion resistance, and so on. The result of evaluation by these features is illustrated in Table 2. The penetration is measured in accordance with the specification as per Japanese standard JIS B 1 125, by the availability of hardness required for penetration through 5.5mm think steel sheet; for the illustration in this table, the mark "O" represents availability of such hardness, and "X" non-availability. The hardness is measured by Micro Vickers at a depth 0.1mm beneath the top layer and by longitudinal section of the tip, or on the surface of longitudinal section if there is a hardened surface layer. Corrosion resistance is measured with the screw being inserted into a piece of EPS (expanded polystyrene) for salt spray test (5% NaCl, 35%, 240h) to check for the presence of pitting or rust; in the table below, "X" represents the presence of pitting and rust, and "O" non-presence.

Figure 2. Tip Hardness vs. Drivable Steel Sheet Thickness



Source: Nippon Steel Monthly, No. 361 (1996)

Table 2. Feature Required of Conventional Self-Drilling and Self-Tapping Screws

Hardening Type	Steel Type	Post-forming Treatment	Tip Hardness (Hv)	Penetration	Corrosion Resistance
Surface Hardening	SUS304	Nitriding + Aluminum & Zinc Plating	1000	O	X
Quenching	Carbon Steels	Carbonizing & Nitriding + Zinc Plating	650	O	X
	SUS304	Nitriding + Tempering	600	O	X
Ageing	SUS304 series	Ageing + Zinc Plating	470～490	X	X
Surface mounting	SUS304	Surface Mounting + Zinc Plating on Carbon Steel Tips	650	O	X

Source: Nippon Steel Monthly, No. 361 (1996)

Conventional self-drilling and self-tapping screws, and by the variety of strength, can be classified into four categories:

Post-forming nitriding as surface hardening process – harness of 1000 Hv is available at the tips for good penetration through steel sheet. Yet, due to nitriding being conducted directly on SUS304 surface, red rust can be seen all over the surface.

Post-forming quenching as strengthening process – hardness up to Hv600~650 is available at the tips for penetration through steel sheet. Despite having been through corrosion resistance treatment, the surface is covered with white and red rust all over.

Ageing treatment after surface hardening – hardness of Hv470~490 at the tips is far from being desirable for penetration. As the screw is zinc plated for the sake of smooth-looking surface, the surface is covered with white pitting and red rust all over.

SUS304 screw with high-strength tip mounted onto it – hardness of Hv650 available at the tips is good for penetration; however, white pitting can be seen all over the head area which is due to surface treatment of zinc plating.

In summary, it can be certain to say that although conventional screw products of SUS304-based stainless steels have Vickers hardness available to penetrate through sheet steels due to their hardening surface treatment, they do not have good corrosion resistance.

Evaluation of Conventional High-strength Stainless Steels by Feature Requirements

Stainless steel with high amount of strength is conventionally applied in the manufacturing of self-drilling and self-tapping screws. We thus evaluate the applicability of stainless steel by categories including the workability in the manufacturing process. The evaluation is detailed below.

Testing materials, testing prototype and evaluation procedures

Prior to the testing, the features of high-strength stainless steels are compiled and classified into four categories by the features of (1) Vickers hardness (Hv), (2) corrosion resistance, (3) cold-forging workability and (4) tool life. The chemical compositions of the stainless steels conventionally used for self-drilling and self-tapping screws applications can be categorized into three groups, as shown in Table 3, including : Austenitic(γ), Martensitic(α'), and Precipitation hardening.

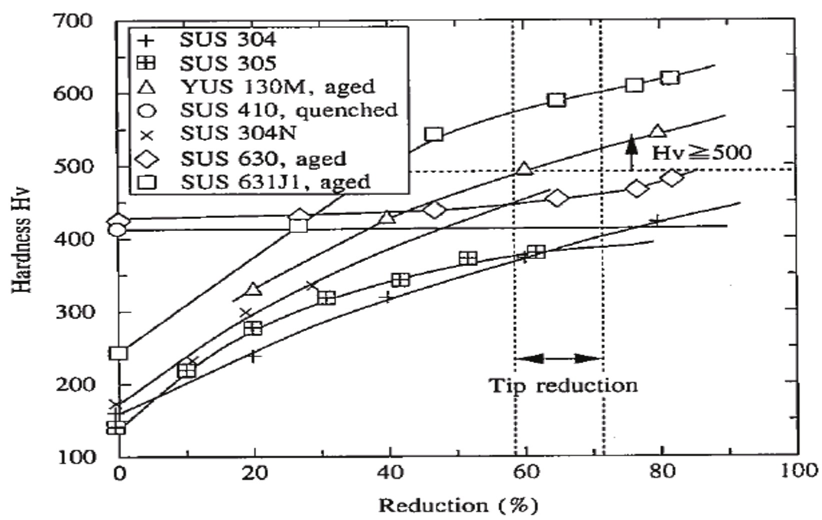
In terms of evaluation on the feature of Vickers hardness, the substrates examined are stainless steels that have been heat-treated after the process of cold-forging. As illustrated in Figure 3, the target hardness of Hv 500 can be achieved by applying cold-forging treatment and ageing at rates equivalent to those for SUS 631J1 and YUS 130M.

Table 3. Chemical Composition of Stainless Steels conventionally used for Self-drilling and Self-tapping Screws Applications

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

Source: Nippon Steel Monthly, No. 361 (1996)

Figure 3. Cold-forging Workability of Conventional Stainless Steel Screws by the Relationship between Hardness and Thickness Reduction



Source: Nippon Steel Monthly, No. 361 (1996)

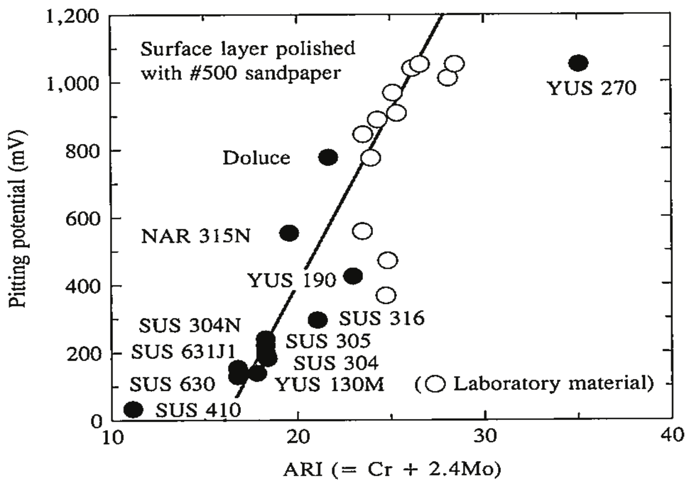
With respect to corrosion resistance, the evaluation can be conducted by using ARI (Anti Rusting Index). The relationship between Anti-Rusting Index (ARI) and Critical Pitting Potential can be expressed, as ARI =Cr+2.4Mo, as shown in Figure 4, in which there exists a positive relation between the values of critical pitting potential and ARI, and that corrosion resistance can be assured in cases when ARI≧18, (equivalent to SUS304 or above).

As to the evaluation of cold-forging workability and tool life, the substrates are evaluated by workability of the substrates prior to screw hardening treatment. The relation between hardness and reduction of thickness, conceptualized as workability, is illustrated in Figure 5, in which SUS305 or SUS410 appear to be the steels that have the lowest workability, inferring that these steels feature better cold-forging workability and tool life.

In summary, YUS130M, SUS305 and SUS410 can be the most desirable types of steels for the applications of self-drilling and self-tapping screws production.

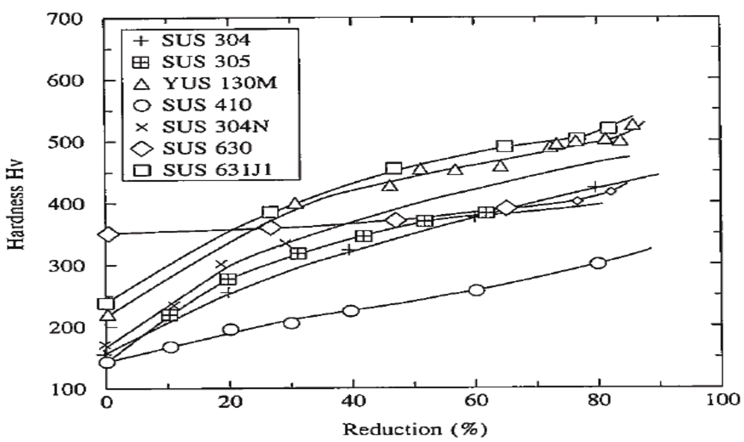
These types of steel wires are then used as the materials for making the prototypes of self-drilling and self-tapping screws. The procedures of prototype making start with the steel wire drawing, annealing to the dimension desired, and cold rolled into self-drilling and self-tapping screws with hexagonal head, and for the sake of availability of hardness for penetration metal sheet through, wires of SUS305 is processed by surface hardening, SUS410 quenching at 1000°C, and YUS130M ageing at 500°C. As welding is not a standard manufacturing procedure, the prototype for the purpose of this study did not include welding procedure for mounting screw sections.

Figure 4. Relationship between Anti-Rusting Index (ARI) and Critical Pitting Potential



Source: Nippon Steel Monthly, No. 361 (1996)

Figure 5. Work-hardening Curvature of Conventional Steel Wires



Source: Nippon Steel Monthly, No. 361 (1996)

The evaluation was conducted by the four categories of penetration, corrosion resistance, cold-forging workability and tool life. The feature of penetration and corrosion resistance is evaluated by utilizing the procedures identical to those for current existing products, and cold-forging workability by whether there is presence of cracks after screw forming, with "X" representing presence and "o" non-presence, while tool life is evaluated by whether there is presence of damage after 5,000 screw forming, with "X" representing presence of damage and "o" non-presence.

The result of evaluation, as shown in Table 4, indicates that surface untreated substrate of SUS305, with merely Hv380~400 at its tip, did not have enough Vickers hardness available for good penetration, despite its good performance in corrosion resistance, workability and tool life.

On the other hand, although surface treated substrate, with Hv1000 at its tip, has sufficient Vickers hardness available for penetration. It did not have good corrosion resistance due to the coating formed by the nitriding process.

Besides, as indicated by the relationship between the thickness of hard surface layer at the tip and the thickness of drivable steel sheet, as shown in Figure 6, the thicker the hard surface layer, the thicker the drivable steel sheet. If a 5.5mm thick steel sheet is to be drivable, then, the hard surface layer must be 60μm thick or thicker. The problem is that it is very difficult to have such thickness available in the industry, given the fact that producing a screw with a hard surface layer up to 60μm thick still requires special type of process.

SUS410 showed good performance with evaluation categories of cold-forge workability and tool life, but not penetration. Its tip hardness being merely Hv420, while the whole body was found to be covered with red rust, indicating the

Table 4. Features of self-drilling and self-tapping screws made experimentally out of conventional stainless steel wires

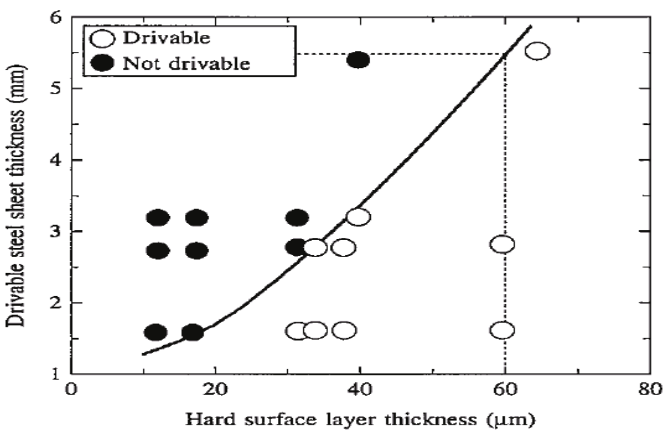
Type of Hardening	Type of Steel	Post-forming Treatment	Tip Hardness (Hv)	Penetration	Corrosion Resistance	Cold-forging Workability	Tool Life
Surface hardening	SUS305	Un-treated	380~400	X	○	○	○
		Tufftriding*1	1000	○	X	○	○
		Tufftriding + Dacromet*2	1000	○	X	○	○
Quenching	SUS410	1000℃ Quenching + Tempering	420	X	X	○	○
Ageing	YUS130M	Ageing (500℃)	470~550	X	○	○	X

Note *1: Salt bath nitriding 550˚C.
*2: Dacromet refers to a coating as a substitute of electrode plating for corrosion protection; it is a thin dry film that is formed, after baking, on the surface of metallic substrate which is coated with water-based chemical composed of passivated zinc, aluminum flakes, chromium anhydrive and acelene dycol.

Source: Nippon Steel Monthly, No. 361 (1996) lack of corrosion resistance in this steel wire material. Another steel wire material YUS130M performed rather well with corrosion resistance and cold-forge workability, but poorly with penetration, with a lack of uniformity as indicated by the variety of tip hardness ranging between Hv460~550. Besides, due to the large extent of work-hardening, the tool life is relatively short.

In summary, self-drilling and self-tapping screws made out of conventional stainless steel wires cannot meet the complete range of requirements that are regarded as necessary features.

Figure 6. Relationship between Hard Surface Layer Thickness （≧1000Hv）and Drivable Steel Sheet Thickness（Substrate 350-400Hv）



Source: Nippon Steel Monthly, No. 361 (1996)

Innovative Stainless Steel Wires for Self-Drilling and Self-Tapping Screws

Since conventional stainless steel wires do not have the kind of features or workability to meet the requirements for the applications of self-drilling and self-tapping screws that call for high level of strength and corrosion resistance, what is left to be hoped for is the modification of chemical compositions for α' series stainless steels, and that makes imminent the developing of innovative stainless steel wires. The problems with the applications of conventional steel wires, if compiled and examined by the aspects of process workability and tool life, lie in the fact that the hardness of SUS305 and YUS130M stainless steels as of γ series is relatively low when screws are being processed, and that means further treatment is required to improve hardness, which is then translated to involving very complex procedures through surface treatment and surface mounting to arrive at the high amount of strength and corrosion resistance required. On the other hand, with the relatively lower work-hardening rate of SUS410 stainless steels as of γ series which meets the requirements on workability and tool life, the challenge however lies in knowing how to improve hardness and corrosion resistance.

In conclusion of the points mentioned above, given the complexity involved in the improving of hardness for γ series stainless steels, it is proposed to use α' series stainless steels instead as substrates, with high amount of hardness and strength achieved by the control of carbon and nitrogen concentration, and corrosion resistance by the control of ARI. Thus, all of the targeted features required of self-drilling and self-tapping screws can all be made available. Therefore, the approach that Japanese industry has taken in the development of innovative stainless steels is to use Martensitic series of stainless steels as the substrate material for the manufacturing applications of self-drilling and self-tapping screws. The topic to be addressed below relates to the innovative materials that the Japanese have developed in the relevant area.

ASL503 by Hitachi

In 1996, the company Miyagawa Metal successfully developed single-piece self-drilling and self-tapping screws, using Martensitic stainless steels as substrate material, with the screw product branded as "Marutex" (Figure 7). The stainless steel material used in this application, a product by Hitachi named ASL503, is a modified variety of Martensitic-based stainless steel containing 13% Cr, featuring lower hardness after annealing and thus allowing good workability, while the hardness and tensile strength is increased up to HRC50 and above through quenching and tempering, allowing penetration through a 12mm thick steel sheet, while featuring shear strength two times as large as quenched and tempered carbon steel screws, and corrosion resistance equivalent to type SUS304, making it suitable for applications of various kinds that require high amount of hardness and corrosion resistance. For reference on the mechanical performance and corrosion resistance of this innovative steel material, see Table 5.

Figure 7.
Marutex Single-piece Self-drilling and Self-tapping Screws

Source: http://www.miyagawa21.co.jp

Table 5. Mechanical performance and corrosion resistance of ASL503 steel

After Annealing	After Quenching and Tempering					
Vickers Hardness (Hv)	Hardness (HRC)	Yield Strength (N/mm2)	Tensile Strength (N/mm2)	Elonga-tion (%)	Drawing (%)	Salt Spray
230	51	1186	1820	14	47	No pitting

Note : Condition of Salt Spray Test, 3.5%NaCl, 35℃, 1000h.
Source: Special Steels, Oct. 1999

Special Steels DSN9 and DSN-PN, by Datung

DSN9 stainless steel features high amount of hardness (high strength) obtained through cold work, yield strength equivalent to type dual-phase stainless steel SUS329J1, and excellent corrosion resistance against attack by sea water, thus allowing application under the sea. Beyond the hardness of Hv500 that is obtained through cold work, DSN9 allows the heat treatment of precipitation hardening to increase its hardness. At the stage of 80% cold work, DSN9 retains its low magnetic permeability ($\mu \leqq 1.01$). DSN9 also features better heat resistance than SUS310, even close to SUH660, thus allowing applications of motor spindles, VTR pilot pins, washers, self-drilling and self-tapping screws, and so forth.

DSN-PN is nickel-free stainless steel that contains high concentration of nitrogen in the group of Austenitic steels. The melting of DSN-PN conducted in pressurized induction furnace contains approximately 1% concentration of nitrogen, but not any amount of nickel, an element hazardous to human health. DSN-PN is applied in wires that require high amount of strength or corrosion resistance, fasteners, non-magnetic components and products in contact with human body. For reference on active ingredients of DSN9 and DSN-PN, see Table 6.

Table 6. Active Ingredients of DSN9 and DSN-PN

	Chemical Composition (mass%)					
Steels	C	Mn	N	Ni	Cr	Mo
DSN9	0.03	6.0	--	10.0	23.0	2.0
DSN-PN	unknown	8	1.2	--	21	4

Source: www.daido.co.jp

YUS550 by Nippon Steel

YUS550 is a stainless steel launched by Nippon Steel in around 1996. As indicated by its chemical composition as shown in Table 7, it contains small traces of N and Mo, as a modified variety of Martensitic steels. Besides the corrosion resistance equivalent to type SUS304, YUS550 features hardness up to 550 Hv that is plausibly achieved by heat treatment, allowing its applications in self-drilling and self-tapping screws, nails required with high amount of strength, various pins and latches, high performance chains and other applications where high amount of hardness and corrosion resistance is required.

YUS550 self-drilling and self-tapping screws are manufactured by the following processes:
Melting→Steel Wire Rolling → Annealing → Wire Drawing → Annealing → Cold Forging → Quenching and Tempering

The tables from Table 8 through Table 11 show data collected from actual applications on the properties of YUS550 by categories of physical properties, mechanical properties, tip hardness and corrosion resistance, respectively. The features include the following:

* High strength (Max. 1800 MPa, Hv600)
* High corrosion resistance (equivalent to 304 stainless steel)
* Excellent workability by cold process (equivalent to 304 stainless steel or above)
* Adequate toughness

The results of using YUS550 as materials for self-drilling and self-tapping screws can be summarized as follows:

In the case of using α' stainless steels, if ARI(Cr+2.4Mo≧)18, and that δ ferrite has been removed, then, the corrosion resistance obtained will be equivalent to or above type SUS304.

In the case of using α' stainless steels, if the effect of carbon on hardness is 2.5 times as much as that of nitrogen, and that $2.5C+N \geqq 0.28\%$, then, hardness Hv550 or above will be obtained.

In the case of using α' stainless steels, the adding of nickel and boron can increase the value of toughness.

The chemical composition of YUS550 is 13Cr-1.5~2.4Ni-2Mo-0.16C-0.1N-0.003B.

Doing two sessions of annealing at a temperature in the vicinity of Acl phase change point can serve as a softening and annealing treatment prior to the forming of the screws by cold-forging process, which allows the hardness to be adjusted to Hv260~300 to facilitate subsequent work on the screws.

After the product having been through heat treatments of quenching at 1150°C and tempering at 200°C, the hardness can reach up to 550Hv, capable of penetrating through 5.5mm thick sheet steels. In addition, given the extremely high temperature at quenching, excessive length of time for quenching process will result in crystalline granules being coarse and enlarged, which will in turn lower the amount of toughness.

Conclusion

The stainless steel materials that are recently developed in Japan have not only seen applications in self-drilling and self-tapping screws, but in fasteners such as latches etc. that require high amount of strength. The challenge, from now on, is to locate potential applications of these steel wires as materials for the manufacturing of a variety of fasteners. The fact that the hardness of these stainless steels obtained by annealing and softening processes is merely Hv260~300 makes it difficult to extend the applications beyond towards parts with contours or complex shapes. Furthermore, to ensure general applicability, the hardness of these steel wire materials must be further reduced so as to ensure cold-forging workability.

References

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2. 「日立金属ねじ用高硬度高耐食ステンレス鋼 ASL503」, Special Steels, October, 1999.

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6.http://www.jicam.com

7.http://www.daido.co.jp

Table 7. Chemical Composition of YUS550

Chemistry (% wt)

	C	Si	Mn	P	S	Ni	Cr	Mo	N
Min.	0.10	-	-	-	-	1.00	12.50	1.80	0.05
Max.	0.20	1.00	1.00	0.040	0.010	2.40	14.00	2.30	0.15

Source:www.jicam.com

Table 8. Physical Properties of YUS550

Physical Properties	Longitudinal Elasticity Coefficient (N/mm2)	Transverse Elasticity Coefficient (N/mm2)	Thermal Expansion Coefficient (cm/°C)
	2.05×10^{5}	7.94×10^{4}	11.5×10^{-5}

Source: www.jicam.com

Table 9. Mechanical Properties of YUS550

Item	Tensile Strength (MPa)	Yield Strength (MPa)	Reduction of Cross-section area (%)	Hardness (Hv)
Annealed Wire	620	450	75	190
Self-drilling & Self-tapping Screws	1750	1150	30	550
Bolts	1000	770	65	350

Source: www.jicam.com

Table 10. Comparison of Hardness with Drill Tips of YUS550

Screw Material	Steel Sheet Thickness	Tip Hardness (Hv) 200 400 600
YUS550	> 5.5mm *	
Type 410	> 5.5mm	
Carbon Steel	> 5.5mm	
Type 202	1.6mm	
Type 304	< 1.6mm	
Type 304 (Nitrided)	< 5.5mm	

* Capable of driving through 10mm thick steel sheet

Source: www.jicam.com

Table 11. Comparison of Corrosion Resistance with YUS550

Screw Material \ Test	Corrosion after Spray Test (5%NaCl, 35°C, 240h)	Corrosion after Sulfurous Acid Gas Corrosion Test (20 cycles as described in DIN 50018-21)	Pitting Potential (mV, vs Ag/AgCl)
YUS550	**No Corrosion**	**No Corrosion**	**250-350**
Type 304	No Corrosion	No Corrosion	200-300
Type 304 (Nitrided)	Red Rust (General)	Black Rust (General)	-300
Type 410	Red Rust (Partly)	Black Rust (General)	0-50
Carbon Steel	Red Rust (General)	Black Rust (General)	-300

Source:www.jicam.com