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Properties of Hot Rolled High Strength Steel Sheets for Automotive Use

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Synopsis :
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There are three methods of increasing the strength of steel: solid solution hardening, precipitation hardening and dual phase (ferrite and martensite) structure hardening. The characteristics of high strength hot rolled steel sheet manufactured by these three methods are examined. Also, the mechanical properties, formability, weldability and fatigue properties of spot welded joints of 60 kgf/mm² class tensile strength hot rolled steel sheet are studied. The dual phase steel sheets have a lower yield ratio, high work hardening rate particularly in the low strain region and excellent properties of elongation and stretch flangeability, compared with conventional high strength steel sheets.

1 Introduction

Against the backdrop of the sharp increase in oil price, strenuous efforts have been made to develop subsitute materials to reduce automotive body weight with a resultant improvement of mileage. Noticeable above all are the development of high strength steel sheet to replace mild steel sheet for reduced thickness without any decrease in car design strength.

In Japan, high strength cold rolled steel sheet is mainly used for outer panels[1-3]. However, further weight reduction is possible if hot rolled steel sheet can be used for parts. Applications of high strength hot rolled steel sheet to frames, reinforcements, bumper supports, members, wheels, etc. are either made practical or under consideration.

In addition to formability, other properties such as surface condition, dentability, weldability, fatigue strength, and paintability are required for automotive steel sheet. To increase C content in steel is the easiest method to render higher strength to steel sheet, but it results in considerable deterioration of formability and weldability. There are two methods of increasing strength of steel sheet: solid solution hardening of Si or Mn and precipitation hardening of Nb, V or Ti. The former requires large amounts of elements to be added for increasing strength, while the latter can attain grain refining hardening and precipitation hardening by applying the processes of controlled rolling and controlled cooling.

Newly developed dual phase steel sheets have been attracting great attention because of their excellent formability-strength combination. The strength of dual phase steel, in which high-carbon martensite islands disperse in fine ferrite matrixes, is proportional to the quantity of martensite as the first approximation. The conventional process of manufacturing dual phase steel consists of heating at the intercritical temperature in order to produce such a state where austenite is dispersed in ferrite, thereby obtaining ferrite and martensite structure by applying critical cooling rate. In addition to this process, a new process for making dual phase steel in as-hot-rolled condition is also developed[4,5].

This report will introduce the manufacturing process of various types of high strength hot rolled sheets and their characteristics, with emphasis on those of 60 kgf/mm² class tensile strength.

2 Manufacturing Process of High Strength Hot Rolled Steel Sheets and Their Characteristics

2.1 Manufacturing Process

Conventional solid solution hardening elements such as Si, and Mn to be added to increase strength of steel require large quantities. Since additions of alloying elements in large quantities deteriorate formability and weldability, high strength steel sheets of the solid solution hardening type have limits to their strength levels.

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Table 1 Comparison of the effects of additives

	Nb	V	Ti
Grain refinement	VS	W	S
Precipitation hardening	VS	S	VS
Inclusion shape control	N	N	S

VS: Very strong, S: Strong, W: Weak, N: No effect

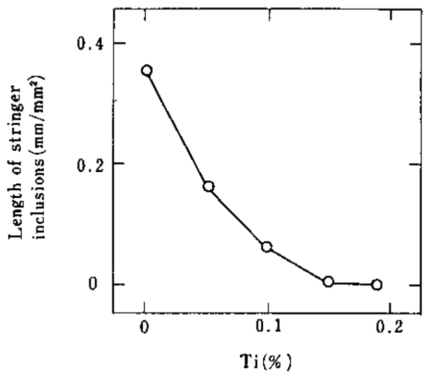

Fig. 1 Effect of the quantities of Ti additions upon stringer inclusion

Characteristics of Nb, V and Ti used for precipitation hardening are shown in **Table 1**. Although Nb has precipitation hardening and grain refining effects, it has no inclusion shape control effect. V has less respective effects than Nb. As shown in **Fig. 1**, Ti, other than the same effects as of Nb, has a remarkable inclusion shape control effect; it improves mechanical properties in the direction perpendicular to rolling and diminishes anisotropy of the steel sheet[6]. While additions of Nb in large quantities result in saturating an increase in strength, Ti can increase strength to a higher level. In order that high strength hot rolled steel of precipitation hardening type makes full use of the properties of elements added, such factors as the slab reheating temperature that prevents austenite from grain growth, hot rolling condition aimed to increase strength by controlled rolling, and coiling temperature that generates fine precipitates, are controlled at optimum levels.

Dual phase steel was first developed as high strength cold rolled steel sheet[7-9]. The CHLY series of Kawasaki Steel are produced by continuous annealing after cold rolling[10-12]. Earlier hot rolled steel sheet also used to be manufactured by continuous annealing after hot rolling; this process was essentially identical to the case of cold rolled dual phase steel sheets.

Recently, as-rolled high strength dual phase steel sheet without continuous annealing process has been developed. Generally, hot rolled steel strip is subjected

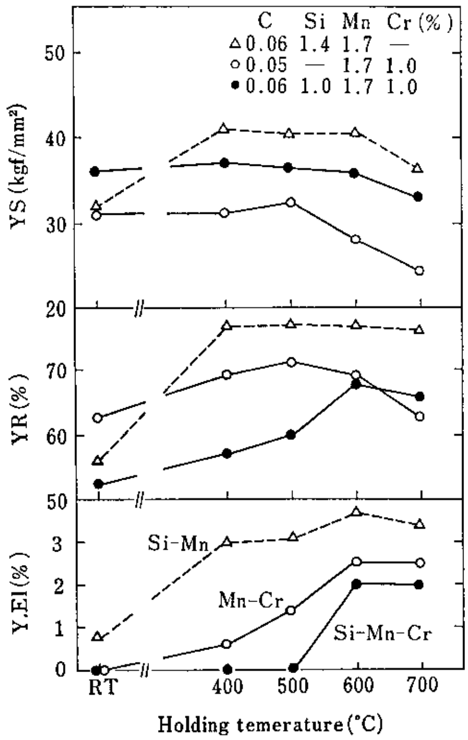

Fig. 2 Effect of the holding temperature after hot rolling upon the mechanical properties of Si-Mn steel, Mn-Cr steel, and Si-Mn-Cr steel (holding time 1 hour each)

to coiling at 500° to 600°C followed by slow cooling. In obtaining the dual phase by this process, however, additions of Mn, Cr, Mo, etc. in large quantities are required to transform austenite into martensite during slow cooling, since the cooling rate after coiling is smaller than that after continuous annealing.

In order to investigate the effect of these alloying elements, changes in mechanical properties by heat treatment of hot rolled steel to which Si, Mn and/or Cr were added have been examined. **Fig. 2** shows the changes in yield strength, yield ratio (ratio of yield strength to tensile strength) and yield elongation with the variation of the holding temperature (simulated coiling temperature) after hot rolling. In the case of the Si-Mn and Mn-Cr steels, yield elongation diminishes when after it is cooled to room temperature, whereas yield elongation never occurs even when Si-Mn-Cr steel is held at 400° to 500°C, with a low yield ratio. Hence, in the case of Si-Mn and Mn-Cr steel, dual phase steel can be obtained by keeping the coiling temperature at ultra low temperatures below 200°C, although such a low coiling temperature deteriorates sheet shape. On the other hand, the behavior of Si-Mn-Cr steel suggests that dual phase steel can be obtained by coiling at 400° to 500°C.

Solute Si in ferrite increases strength without losing

Table 2 Typical mechanical properties of high tensile strength hot rolled sheets, 2.3 mm thick

Type	Class	Tensile properties					n_{5-15}	$\bar{r}$	Notched tensile Elongation(%)	Hv	Minimum bend radius
		YS (kgf/mm²)	TS (kgf/mm²)	El (%)	Y.El (%)	YR (%)					
Precipitation hardening	50	47.6	54.3	30	1.8	88	0.149	0.90	8.6	162	0t
	55	49.7	57.2	28	2.2	87	0.134	0.98	7.7	160	0t
	60	54.0	62.3	29	3.4	87	0.175	0.94	7.2	189	0t
Solution hardening	50	36.9	50.0	35	1.1	74	0.191	0.94	11.2	147	0t
	55	43.5	55.0	32	2.0	79	0.206	0.89	10.1	157	0t
Dual phase	55	31.5	55.1	35	0	57	0.225	0.83	11.0	151	0t
	60	35.9	61.0	34	0	59	0.220	0.83	9.7	156	0t
	65	37.8	66.9	32	0	57	0.209	0.83	9.3	178	0t

Table 3 Chemical compositions of steel sheets in Table 2

(wt%)

Type	Class	C	Si	Mn	P	S	Ti	Cr
Precipitation hardening	50	0.08	0.04	0.96	0.015	0.003	0.03	
	55	0.04	0.04	1.07	0.017	0.003	0.05	
	60	0.05	0.55	1.25	0.019	0.003	0.06	
Solution hardening	50	0.06	0.53	1.45	0.019	0.003		
	55	0.08	0.52	1.58	0.022	0.003		
Dual phase	55	0.05	0.49	1.24	0.018	0.004		1.03
	60	0.05	1.03	1.30	0.021	0.003		1.06
	65	0.05	1.00	1.40	0.022	0.003		1.03

ductility much. Si, Mn and Cr cause carbon segregation into austenite from ferrite. Moreover, Mn and Cr stabilize the austenite during slow cooling and make it easy to obtain dual phase structure having ferrite matrixes with high ductility and hard-martensite phase with high strength. Especially, Cr has an additional effect of slightest increasing yield strength through solid solution into the ferrite phase. It follows, then, that dual phase steel can be obtained at the condition close to the normal coiling temperature through the optimum combination of three alloying elements.

2.2 Comparison of Properties of Steel Sheets Hardend with Various Mechanisms

Mechanical properties of three types of steel sheet whose tensile strength are 50 to 65 kgf/mm² are listed in **Table 2**: the solid solution hardening type using Si and Mn; the precipitation hardening type mainly with addition of Ti; and dual phase type. Chemical compositions of these sheets are shown in **Table 3**.

Values of various properties were arranged in terms of tensile strength in order to compare differences in properties according to the hardening method. The relations between tensile strength and yield strength are illustrated in **Fig. 3**. The yield ratio of the precipitation hardening type steel sheet is the largest, while that of the dual phase steel sheet is the smallest. In other words, the precipitation hardening type steel sheet is suitable for parts having large area of underformed region and requiring high yield strength. On the other hand, the dual phase steel sheet with a low yield strength has a small spring back after forming.

Fig. 4 shows the relations of tensile strength with work hardening rate *n*, elongation and notched tensile elongation. For notched tensile elongation, 2 mm V notches were made on both edges of the center of a JIS No. 5 tensile specimen in which main axis is perpendicular to the rolling direction; fracture elongation was measured between the points of gage length of 50 mm. A comparison at an identical level of strength shows that the dual phase steel sheet has the highest

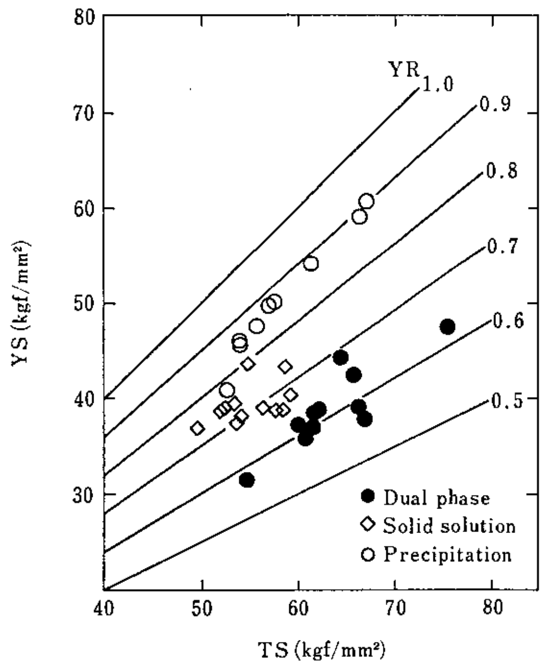

Fig. 3 Relation between tensile and yield strength

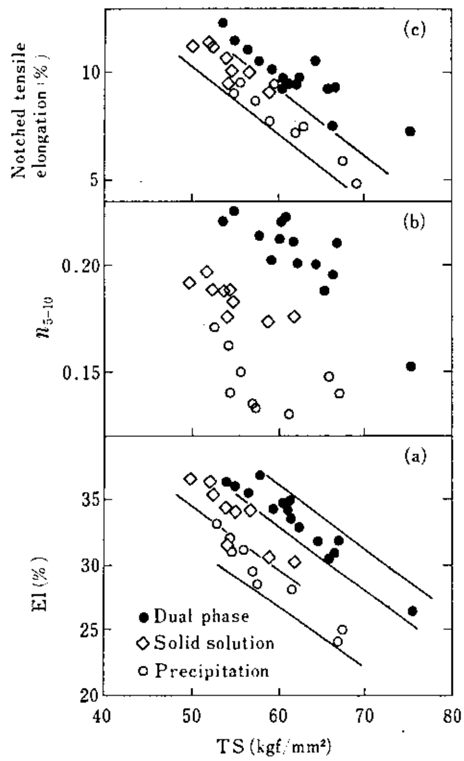

Fig. 4 Relations of tensile strength with work hardening rate n, elongation, and notched tensile elongation

for both elongation and n-value, followed by the solid solution hardening type steel sheet and precipitation hardening type steel sheet in the decreasing order. Since notched tensile elongation is an index showing stretch flangeability, it can be said that the dual phase steel sheet has high stretch flangeability.

3 60 kgf/mm² Class Tensile Strength Hot Rolled Steel Sheet

3.1 Mechanical Properties

Fig. 5 shows stress-strain curves of 60 kgf/mm² class high tensile strength hot rolled steel sheets (HTP 60F-APFH 60: solid solution and precipitation hardening steel sheet, HTP 60D-HHLY 60: dual phase steel sheet). The stress-strain curve of plain carbon steel (SAPH 41) is also shown for comparison. While HTP 60F has high yield strength, HTP 60D does not show a definite yield point and has a continuous stress-strain curve with a large uniform elongation. Strain dependence of the work hardening rate is presented in **Fig. 6.** The work hardening rate of HTP 60D is larger than that of HTP 60F, and this is particularly outstanding in the low strain region. It suggests that HTP 60D excells in shape fixability with a small spring back after press forming.

A comparison of microstructures of HTP 60F and HTP 60D with SAPH 41 is shown in **Photo. 1.** Their chemical compositions are listed in **Table 4.** The grain diameter of the high strength steel sheet is smaller than that of SAPH 41. The gray phase of HTP 60D is

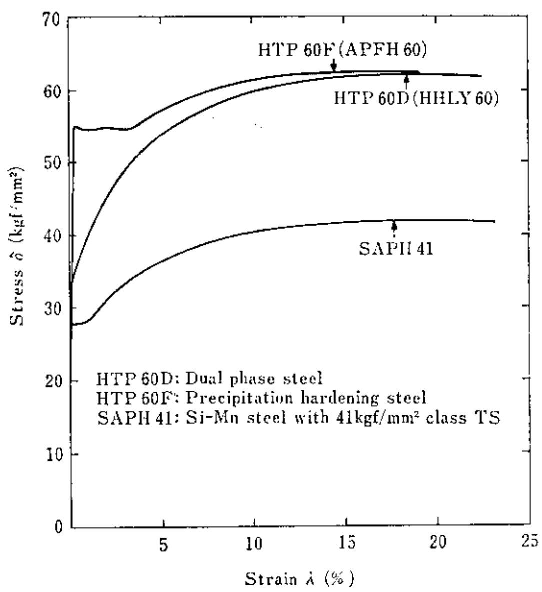

Fig. 5 Stress-strain curves of 60 kgf/mm² class tensile strength hot rolled steel sheets

martensite. The grain size of HTP 60F is very fine due to controlled rolling and the grain refining effect of Ti.

In order to investigate the properties of ageing and bake hardenability, changes in yield strength and tensile strength were measured in two different conditions: one with no pre-strain and the other with a 10% pre-strain in tension followed by ageing for 30 min. at various temperatures above 100°C. The temperature dependence of strength is illustrated in **Fig. 7(a)** and **(b)**.

Each steel sheet without prestrain exhibited no change in yeild strength at less than 150°C and no room temperature ageing took place. When heated to over 200°C, however, HTP 60D had its yield strength

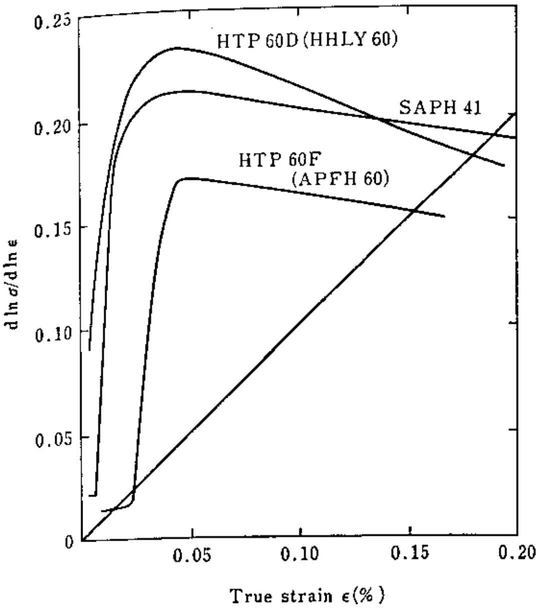

Fig. 6 Strain dependence of the work hardening rate of 60 kgf/mm^2 class tensile strength hot rolled steel sheets

Table 4 Chemical compositions of 60 kgf/mm^2 class tensile strength hot rolled steel sheets, 2.6 mm thick

(wt%)

Steel	C	Si	Mn	P	S	Ti	Cr
SAPH 41	0.12	0.03	0.80	0.022	0.013	—	—
HTP 60F(APFH 60)	0.05	0.55	1.25	0.017	0.004	0.06	—
HTP 60D(HHLY 60)	0.06	1.03	1.33	0.021	0.003	—	1.06

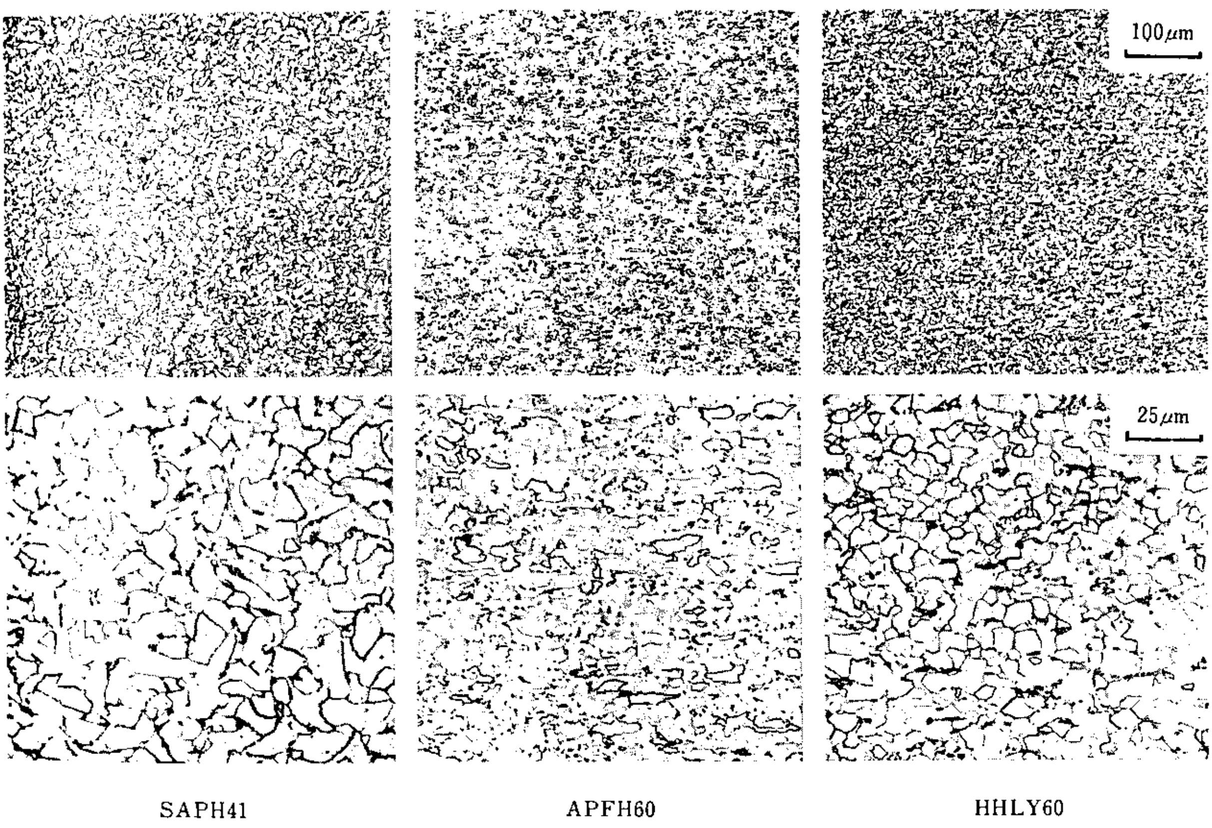

Photo. 1 Optical microstructures of high strength steel sheets

increasing sharply and reaching the maximum value at 300° to 400°C, whereas that of HTP 60F hardly underwent any change. When pre-strain was given, yield strength rose very high because of high work hardening, particularly, in the case of HTP 60D, and the increase in yield strength due to age hardening appeared at temperatures above 200°C. In other words, hardening during the paint baking process after forming can be expected at temperatures only over 200°C but it is small at temperatures below 200°C.

To obtain a forming limit diagram, the uniaxial tension, plane strain, and bi-axial tension tests were conducted. 5 mmϕ grid marks were used for this experiment. The results are shown in **Fig 8**. The formability of the high strength steel sheet is inferior to that of the mild steel (SAPH 32). However, HTP 60D has superior bi-axial stretch forming to that of HTP 60F, presumably because HTP 60D hasi a high work hardening rate. The 60 kgf/mm² class tensile strength hot rolled steel sheets are currently beng evaluated in various automotive parts forming trials and applications, as shown in **Photo. 2**.

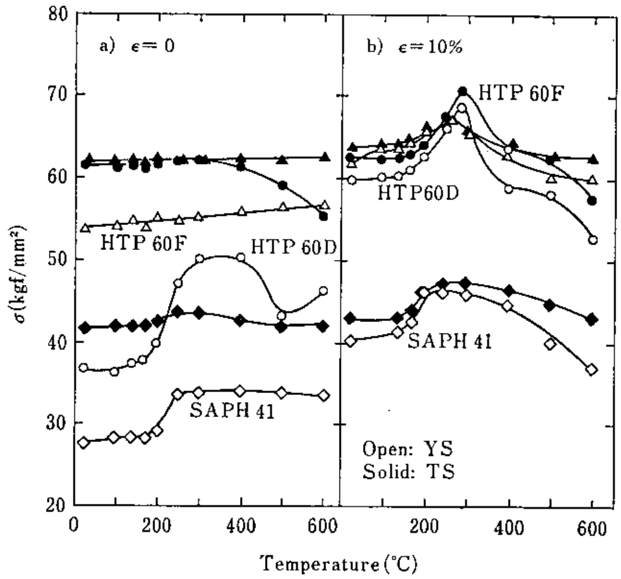

Fig. 7 Changes in yield and tensile strengthes of high strength steel sheet due to ageing
a) No pre-strain
b) 10% tensile pre-strain

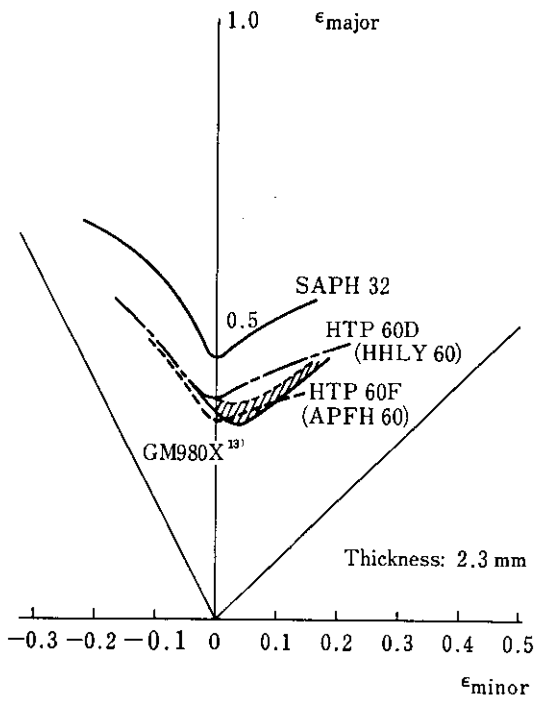

Fig. 8 Forming limit diagram of 60 kgf/mm² class tensile strength hot rolled steel sheet

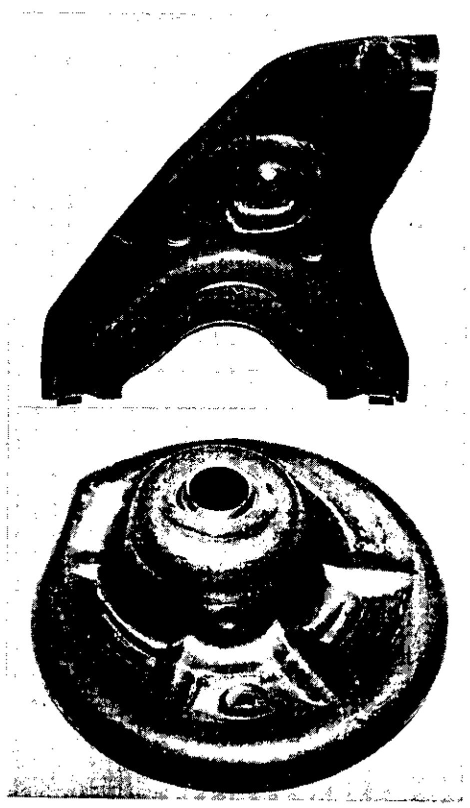

Photo. 2 Examples of formed automotive parts using high strength hot rolled steel sheets:
Upper; Rear arm formed from HTP 60D-HHLY 60 (as-rolled dual phase steel) of 2.3 mm thickness
Lower; Seat upper front spring formed from HTP 60F-APFH 60 of 2.3 mm thickness
By the courtesy of Nissan Motor Corporation

3.2 Spot Weldability

The hot rolled steel sheet was subjected to pickling and spot welding in order to examine the spot weldability of high strength steel sheet. With welding time of 26 cycles and holding time of 15 cycles set constant, the welding current and electrode force were varied to determine the critical curves for expulsion. The result is presented in **Fig. 9**. In the case of high strength steel sheet, the critical curve of expulsion moves to the low current side at the same welding force compared with mild steel. Because of considerable amounts of alloying elements, the expulsion limit of HTP 60D is at lower current than that of HTD 60F. Spot welding was applied at the current slightly lower than that of the expulsion limit and the results such as the static tensile shear strength and the cross tensile strength are described in **Table 5**. Changing the welding condition will not appreciably alter the strength of welded joints. The tensile shear strength increases in proportion to the strength of the parent metal. Ductility ratio, D.R. (ratio of the cross tensile strength to the tensile shear strength) of HTP 60D is somewhat low.

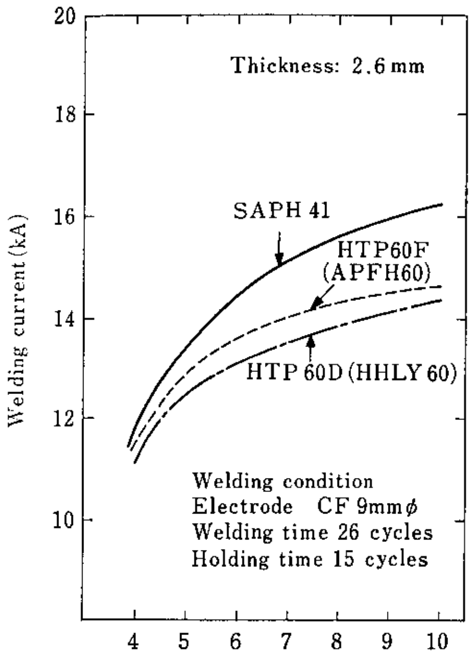

Fig. 9 Critical curves for expulsion in spot welding

It is well known that the fatigue strength of high strength steel sheet increases proportionately to the static strength of the parent metal. And yet, there are not many reports on fatigue strength of the welded joints. Therefore, the fatigue specimen was made from two pieces of sheet of 2.6 mm thickness jointed together with a single spot welded. Spot welding conditions

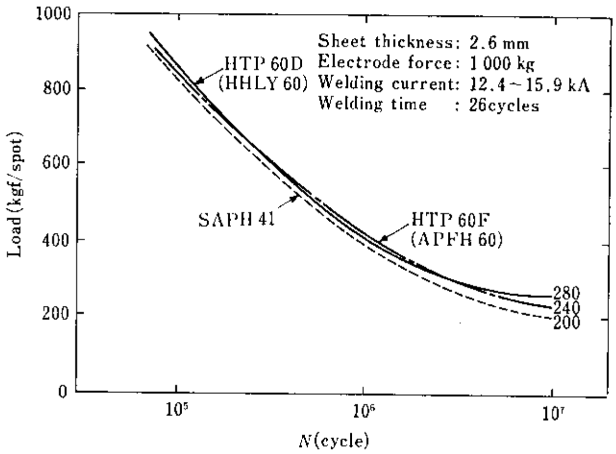

Fig. 10 Tensile shear fatigue curves of the spot welded joints

Table 5 Static properties of spot welded joints of hot rolled steel sheets, 2.6 mm thick

Steels	Welding condition			Strength of welded joints			Tensile properties of base steels		
	Time (cycle)	Force (kgf)	Current (kA)	TTS (kgf)	CTS (kgf)	DR (%)	YS (kgf/mm^2)	TS (kgf/mm^2)	El (%)
SAPH41	26	650	14.5	3210	2510	78	27.8	41.7	41
	26	1000	15.6	3260	2600	80			
HTP60F (APFH60)	26	650	13.3	4620	3440	74	54.5	62.2	28
	26	1000	14.2	4110	3270	79			
HTP60D (HHLY60)	26	650	13.0	4380	2800	64	35.0	62.1	33
	26	1000	14.0	4450	2970	67			

are as follows: the welding force of 1 000 kgf, a welding time of 26 cycles and the current just below critical curve for expulsion. The fatigue test was of the tensile shear fatigue, load control type: 0-tensile load was applied at 1 800 rpm. Load-cycle curves are shown in **Fig. 10**. The fatigue strength of the spot welded joints of three kinds of steel sheet shows no appreciable difference, be it 60 kgf/mm^2 class or 41 kgf/mm^2 class, conceivably because high strength steel sheet has a high notch sensitivity. But the endurance limit of high strength steel sheet is slightly at high levels.

4 Summary

The manufacturing process of high strength hot rolled steel sheet and its characteristics were briefly introduced, and the properties of 60 kgf/mm^2 class tensile strength hot rolled steel sheet was mainly summarized. It was made clear that as compared with conventional high strength steel sheets, the newly developed dual phase steel sheet had a low yield ratio, high work hardening rate particularly in the low strain region, and excellent properties of elongation and flangeability. Consequently, it has superior formability, especially in the stretch forming section, to that of the conventional high strength steel sheets.

As far as its spot weldability is concerned, its critical limit current for expulsion is somewhat low because it contains more alloying elements than the conventional high strength steel sheets. So long as appropriate welding conditions are selected, however, strength of the welded joints is nearly the same. As for fatigue strength of welded joints, there is hardly any difference between the conventional high strength steel sheet and the dual phase steel sheet: fatigue strength of welded joints of 60 kgf/mm^2 class tensile strength steel sheet was approximately the same as that of 41 kgf/mm^2 class tensile strength steel sheet.

High strength hot rolled sheet has been used for truck frames and booms of truck cranes. Demand for further reduction of car body weight will be certain to continue; and because higher strength hot rolled steel sheet contributes greatly to reducing weight, it will draw more attention.

Kawasaki Steel manufactures various types of hot rolled steel sheet (50–100 kgf/mm^2 class tensile strength) and can supply steel sheets best suited to each application. It is hoped that such high strength steel sheet will go a long way toward conserving resources and saving energy.

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