KAWASAKI STEEL TECHNICAL REPORT

No.25 (September 1991)

Special Issue on 'H-Shapes with

Fixed Outer Dimension' and 'Steel Pipe'

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The body can be viewed from the next page.

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1 Introduction

When H-shapes are used as such structural members as beams and columns, a very economical design can be obtained by minimizing the web thickness, because the contribution of the web to bending stiffness is very small. For this reason, the requirement for light-web H-shapes is increasing.

H-shapes manufactured by welding plates (welded H-shapes) have the advantage that shape defects such as web buckling are less likely to occur because of the low residual stress generated by welding. Consequently, their web thickness can be reduced relatively easily. In contrast to this, H-shapes manufactured by hot rolling (rolled H-shapes), in which a temperature difference between the web and flange exists due to thickness difference in the rolling and cooling processes, can suffer from the residual stress in the longitudinal direction (compressive stress in the web and tensile stress in the flanges).[1,2] Reducing the web thickness in rolled H-shapes increases the residual stress and reduces the critical buckling stress of the web so that web buckling can occur. Furthermore, because the rolling temperature of the web becomes lower, a deterioration in material quality such as an increased yield ratio (yield stress/tensile stress) may occur. These problems make it difficult to obtain light web rolled H-shapes and, as shown in **Fig. 1**, only welded H-shapes have hitherto been supplied in light-web section. If light-web H-shapes can be manufactured by rolling, the merits of low production cost and stable quality of fillet (the boundary between the flange and web) can be achieved.

Kawasaki Steel has devoted great effort for many years to develop the technique for manufacturing light-web rolled H-shapes. As a result, it has become possible to produce light web H-shapes by conducting tandem

* Originally published in *Kawasaki Steel Giho*, 23(1991)1, 23-28

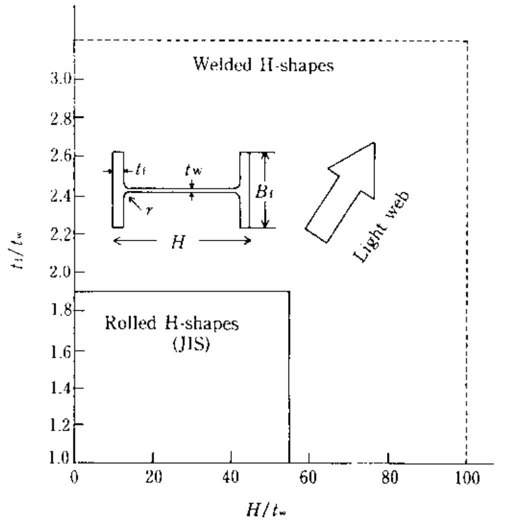

Fig. 1 Comparison of product size between rolled and welded H-shapes

rolling in roughing universal mills (RU mills) and cooling the flange with water before and after the finishing universal mill (FU mill). This technique for obtaining light webs is detailed in this report.

2 Selection of the Method for Obtaining Light Webs

To obtain light webs in rolled H-shapes, it is necessary to prevent web buckling by reducing the residual stresses. This can be accomplished by minimizing the temperature difference across the section in the universal finishing mill, and the cooling rate difference between the flange and web after rolling. To ensure good web quality, it is necessary to maintain the finishing temperature above a certain level. Several methods are available as the means to meet these requirements.

2.1 Reduction of Residual Stress

2.1.1 Water cooling of flange

It is well known that the residual stress can be substantially reduced if the flange with relatively large thickness is cooled by water before or after rolling in an FU mill.[3-6] This flange cooling before FU rolling reduces the residual stress by decreasing the final finishing temperature difference between the flange and web, which reduces the thermal contraction difference between the flange and web during cooling from the temperature existing immediately after rolling to room temperature. On the other hand, the flange cooling after FU rolling reduces the residual stress by utilizing the plastic strain difference existing between the flange and web that is generated by thermal stress during the cooling process after rolling. However, if the inner surface of the flange is cooled by water, this water may also cool the upper surface of the web and increase the temperature difference; therefore, water cooling should only be applied to the outer surface of the flange. The cooling method chosen must be such that the transverse temperature distribution across the flange is kept uniform, that web buckling is prevented, and that no deterioration of material quality occurs.

2.1.2 Heat retention and heating of web

The temperature difference between the flange and web decreases if heat can be retained in a light web by using a mirror or insulation[3,7] or by induction heating.[8] Then the residual stresses can be reduced based on the same concept as in the case of water cooling of the flange. However, compared with the water cooling of the flange, the method of web heating has a smaller effect on reducing the residual stress, resulting in longer processing time and reduced productivity (especially in the case of heat retention), and in increased production cost from the electric power needed (in the case of induction heating).

2.1.3 Low-temperature finishing rolling[9]

Tensile rolling (flange reduction > web reduction) at a relatively low temperature (below 650°C), at which the plastic strain by rolling remains, allows the difference in thermal contraction between the flange and web from the after-rolling to room temperature to be balanced with the plastic strain difference, thereby reducing the residual stress. This method can, however, degrade the mechanical properties by increasing YR and decreasing the toughness.

The method for reducing the residual stress can be chosen from the three foregoing methods. Water cooling of the flange was selected by Kawasaki Steel because productivity would be maintained and the method would have a large effect on reducing the residual stress and preventing web buckling.

2.2 Ensuring Material Quality for Web

2.2.1 Tandem rolling in roughing universal mills

By using tandem RU mills, the rolling time can be reduced and higher web finishing temperatures can be obtained in RU rolling and FU rolling. Kawasaki Steel could conduct tandem rolling relatively easily by converting a conventional edger mill into a universal mill through the adoption of an attached edger mill.[10] Tandem rolling has the additional advantage of the rolling efficiency being improved, in addition to preventing the drop in web temperature.

2.2.2 Web heating

To ensure a sufficiently high web finishing temperature in the web during RU rolling or FU rolling, it is possible to heat the web at the entry side of the RU or FU mills. Compared with tandem rolling, however, web heating suffers from a decrease in the rolling efficiency due to the heating time required and an increase in the production cost by the use of electric power.

Although both these methods can ensure material quality for the web, tandem rolling in RU mills was adopted because of its better rolling efficiency.

3 Study on Water Cooling of Flange

3.1 Water Cooling Method of Flange

It is necessary to establish a cooling method that efficiently reduces the residual stress to prevent the web buckling without causing any deterioration of material quality.

When rolling H-shapes, the middle of the flange has the highest value in the transverse temperature distribution before water cooling because of the large thickness of the fillet. In order to efficiently reduce the residual stress, therefore, it is advantageous to make the flange temperature close to the web temperature after making the transverse flange temperature distribution uniform. Furthermore the flange must be cooled by water on its outer surface only, because any water that gets on the web lowers the web temperature and can increase the temperature difference between the flange and web. As shown in **Fig. 2**, flat water cooling, by which the greater part of the flange width is cooled, and spot water cooling, by which the center of the flange is mainly cooled, are conducted alternately in the longitudinal direction to obtain a uniform transverse flange temperature distribution. These two patterns of water cooling permit independent water flow control, and vertical adjustment of the cooling nozzle position in the transverse direction of the flange is also possible. This vertical adjustment of the cooling nozzle position is necessary to prevent excessive cooling of the lower part of the flange due to dropping water.

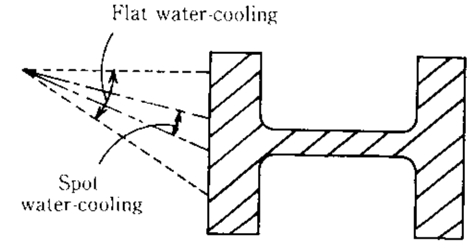

Fig. 2 Method for cooling flange by water

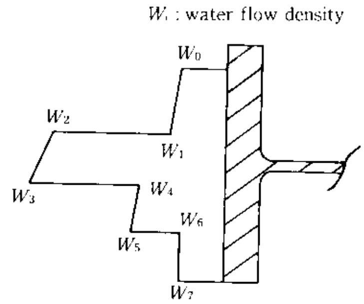

Fig. 3 Schematic distribution of water-flow density

3.2 Simulator for Analyzing Temperature and Thermal Stress

Kawasaki Steel developed an analytical simulator to predict both the temperature and thermal stress during water cooling of the flange. This allowed the detailed specifications of flange water cooling equipment (location and length of the equipment, water flow density, spray width, etc.) to be examined. This simulator was developed by expanding the functions of another simulator[1] that had already developed by the authors. The features and outline of the new simulator are given below.

(1) The temperatures in the section are calculated according to the alternating direction implicit difference method[11] by neglecting the heat flow in the longitudinal direction.

(2) Elastic-plastic stress analysis is made by presuming generalized plain strain in the longitudinal direction.

(3) The deflection at room temperature is predicted by analyzing 1/2 of the section of an H-shape.[12]

(4) Whether the web buckles or not is calculated from the distribution of compressive thermal stress in the web.

(5) The water flow density in the transverse direction of the flange for both flat water cooling and spot water cooling is calculated (**Fig. 3**).

(6) The heat transfer coefficient during water cooling is calculated from the water flow density.

(7) The phase transformation is calculated from an isothermal transformation curve, and changes in the material properties (specific heat, thermal conductivity, latent heat of transformation, coefficient of linear expansion, and yield stress) are also taken into consideration.[13]

(8) The mechanical properties (tensile strength, yield stress, elongation and hardness) at room temperature are predicted.[14]

Items 3, 5, 6 and 8 are new functions added to those of the original simulator. The whole flow of calculation procedure by the simulator is shown in **Fig. 4**.

To examine the predicted accuracy of the simulator, a comparison was made between calculated and measured values of the surface temperature at the delivery side of the FU mill and of the residual stress in H-shapes with water-cooled flange. The results are shown in **Figs. 5** and **6**. Flange water cooling was done between the RU and FU mills. The temperature was obtained by measuring the outer flange surface with a radiation pyrometer, and the residual stress (average value across thickness) with strain gauges. The standard deviation

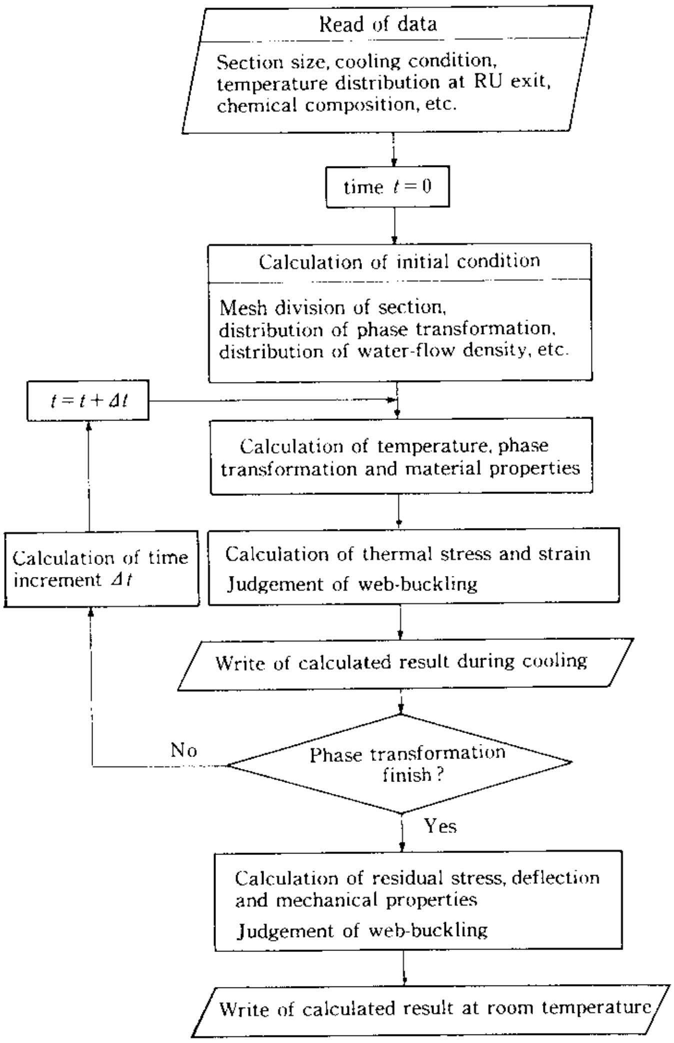

Fig. 4 Whole flow of the mathematical simulator

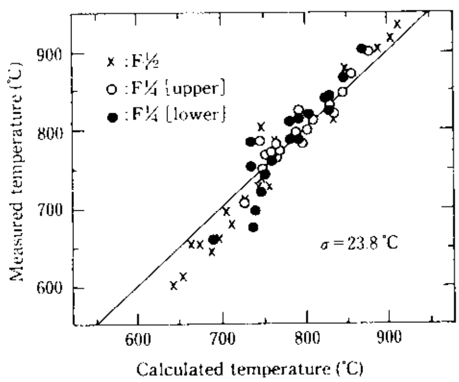

Fig. 5 Comparison between calculated and measured temperatures on outer flange surface

(σ) of the difference between measured and calculated values was 24°C for the temperature and 39 MPa for the residual stress. Both the temperature and residual

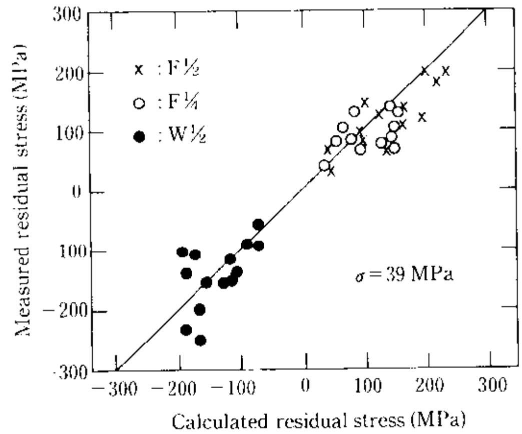

Fig. 6 Comparison between calculated and measured residual stresses

stress can be predicted with considerable accuracy even when flange water cooling is applied.

3.3 Specifications of Flange Water Cooling Equipment

The specifications of the flange water cooling equipment for light-web H-shapes were studied by using the analytical simulator. The dimensions of the light-web H-shapes used are given in **Table 1**, and criteria for determing on specification of the water cooling equipment are given in **Table 2**. The results of the study are summarized as follows:

(1) To manufacture light-web H-shapes, it is necessary to install the flange water cooling equipment between the RU and FU mills and after the FU mill.
(2) The cooling characteristics should be such that strong water cooling is conducted between the RU and FU mills and weak water cooling is conducted after the FU mill.
(3) It is necessary to divide the water cooling equipment between the RU and FU mills into three zones, and the water flow density must be capable of being independently controlled for each zone.
(4) To prevent shape defects (web buckling, bending and twisting) and to obtain the required mechanical properties, it is necessary to use both flat and spot water coolings.
(5) To prevent bending and twisting, it is necessary to adjust the vertical position of the cooling nozzles across the flange depending on the water cooling conditions.
(6) Steel grade SS400 requires stronger water cooling than steel grade SM490.

Based on the results of this study, the water cooling equipment shown in **Fig. 7** was installed at the company's Wide-flange Beam Plant. The specifications of the water cooling equipment are shown in **Table 3**.

Table 1 Dimension of light-web H-shapes

Thickness ratio (t_f/t_w)	≦3.0
Web depth (H)	400～900 mm
Flange width (B_f)	150～300 mm

Table 2 Criteria for determining on specification of water-cooling equipment

Item	Criterion
Web wave by buckling	Not occurred
Microstructure	Ferrite+Pearlite (No Martensite and Bainite)
Deflection amount	≦10 mm/10 m-length
Residual stress at center of web	≦100 MPa

Table 3 Specifications of water-cooling equipment

Zone No.	Length (m)	Flat spray		Spot spray	
		Width (mm)	Water flow density (l/m²·min)	Width (mm)	Water flow density (l/m²·min)
1	30	150	900～2 000	40	400～900
2	20	150	600～1 350	40	400～900
3	20	150	600～1 350	40	400～900
4	20	100	400～900	60	250～550

4 Study on Tandem Rolling in Roughing Universal Mills

The decrease in web rolling temperature due to light web cause a deterioration in the material quality of the web, in addition to the above-mentioned residual stress problem that causes web buckling. Here, a deterioration of the material quality means an increase in the yield ratio (YR). As shown in **Fig. 8**, the increase in YR becomes marked when the RU finishing temperature of the web is below the Ar_3 transformation point. Although the effect of the FU finishing temperature on the material quality is conceivable, it might be thought that the material quality would hardly change because

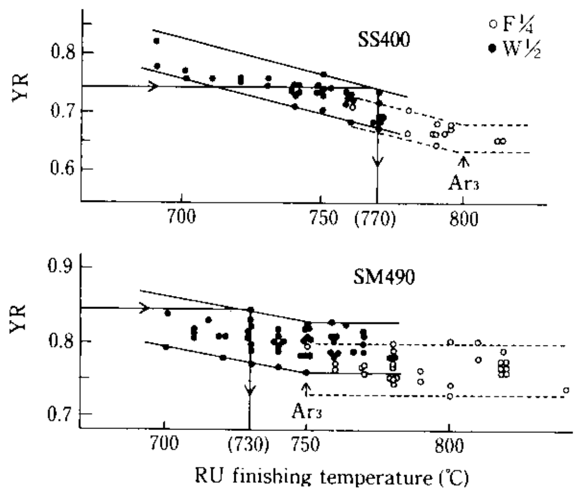

Fig. 8 Relation between RU finishing temperature and YR

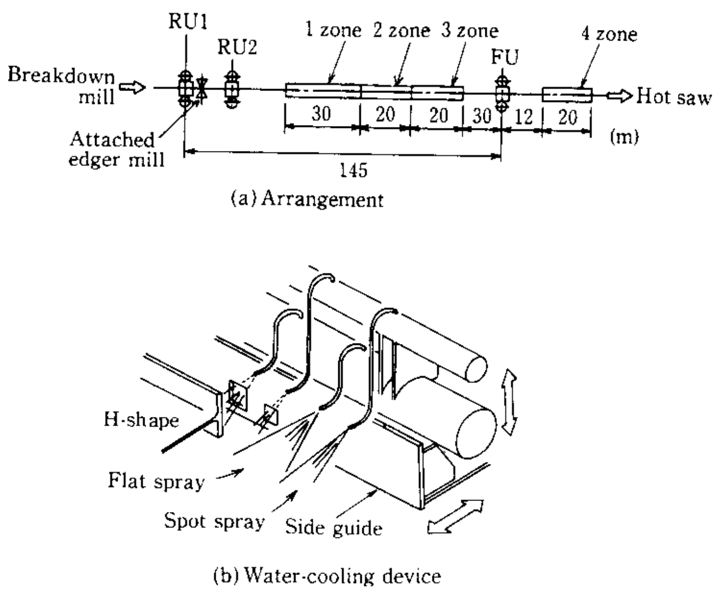

Fig. 7 Water-cooling equipment

the web reduction in a usual FU rolling is as low as a few percent.

Although a standard for the YR value in H-shapes has not yet been clarified, a YR requirement of not more than 80% is being put forth for the flange of SM490 class as with plates. It is desirable that the web has the same material quality as the flange if rolled H-shapes are used as a substitute for welded H-shapes. However, it is particularly difficult to obtain the same material quality in the web and flange because of the rolling characteristics that the web is generally rolled at a lower temperature than the flange. For this reason and because of the low contribution of the web as a structural element, +5% to the YR of the flange was set as the target YR for the web. It is apparent from Fig. 8 that the temperature range in which this target YR is attainable is about 730°C or more for SM490 and about 770°C or more for SS400.

A study was made of whether tandem rolling by two RU mills would give the required temperature for an extra-light web thickness of 6 mm, using the existing rolling temperature simulator.[15] First, a comparison was made between the calculated and measured values of surface temperature at the entry side of the RU mill immediately before each pass. The results of the comparison are shown in **Fig. 9**, and it is apparent that the rolling temperature can be predicted with sufficient accuracy for application to tandem rolling.

The effect of the as-rolled length and number of passes on the web finishing temperature in the RU mill was checked for both tandem rolling and single-mill rolling. The results shown in **Fig. 10** can be summarized as follows:

(1) The web finishing temperature was far higher with tandem rolling than with single-mill rolling.
(2) The longer the as-rolled length and the larger the number of passes, the lower the web finishing temperature. This tendency was more marked for single-mill rolling than for tandem rolling, the effects of the as-rolled length and number of passes on the web finishing temperature being small for tandem rolling.
(3) With single-mill rolling, it was impossible to ensure a web finishing temperature of 770°C or more that did not cause a deterioration in the material quality of SS400, and an as-rolled length of 100 m or more that did not reduce the production efficiency and product yield. However, this was possible with tandem rolling in 18 or fewer passes.

The number of passes is limited by the mill capacity (rolling force, rolling torque and rolling power), although the smaller the number of passes, the higher the rolling efficiency. Eighteen passes are required to manufacture an H-shape of 550 × 200 × 6 × 9 mm by tandem rolling in two RU mills at the Wide-flange Beam Plant.

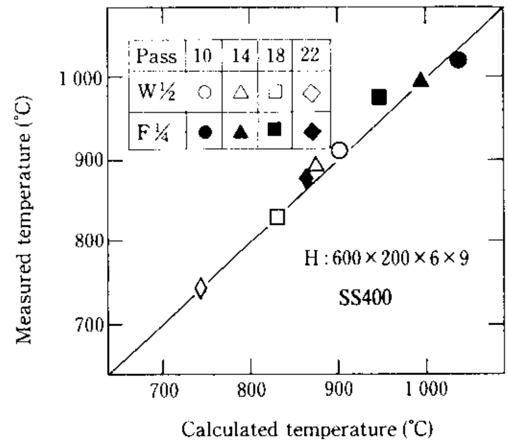

Fig. 9 Comparison between calculated and measured surface temperatures at RU1 mill entry

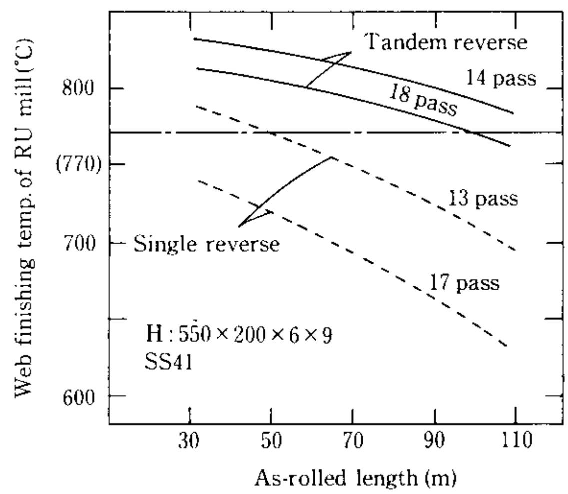

Fig. 10 Influence of as-rolled length and pass number on web finishing temperature of RU mill

5 Equipment for Manufacturing Light-Web H-Shapes

The manufacture of light-web H-shapes at the Wide-flange Beam Plant necessitated installing water cooling equipment between the RU and FU mills and after the FU mill. The existing RU mill was also converted into a two-stand tandem units. This equipment has enabled light-web H-shapes to be manufactured to the required standard. **Table 4** gives the manufacturing conditions and product quality as a typical example for the H-shape of 550 × 200 × 6 × 16 mm that is the most difficult to manufacture.

Table 4 Manufacturing conditions and product qualities (H: 550 × 200 × 6 × 16 mm)

	Steel grade	SM490
Manufacturing condition	Pass number BD RU1+RU2 FU	 9 18 1
	Water flow density (l/m²·min) Flat spray Spot spray	[1 zone] [3 zone] [4 zone] 1 000 1 000 800 400 400 300
	Shape defect Web buckling Twist Deflection	 Not occurred Negligible Negligible
	Dimension accuracy	Equivalent to that of welded H-shape
Product quality	Mechanical Properties TS (MPa) YS (MPa) El (%) HV	 520～570 (490～610)*1 370～400 (≧320)*1 20～26 (≧17)*1 163～177
	Residual Stress (MPa)	≦50

( )*1: JIS

6 Conclusions

A process for manufacturing light-web rolled H-shape has been investigated. The result obtained are as follows:

(1) To obtain light webs, it was necessary to prevent web buckling by reducing the residual stress, and to prevent a deterioration in the material quality by avoiding a drop in the web rolling temperature.

(2) The residual stress was reduced by water cooling the flange between the RU and FU mills and after the FU mill.

(3) The web temperature was maintained by tandem rolling in RU mills.

Based on the above result, water cooling equipment was installed between the RU and FU mills and after the FU mill at the company's Wide-flange Beam Plant, and the existing RU mill was converted into a two-stand tandem RU unit. This equipment now produces rolled H-shapes with a much lighter web than JIS H-shapes.

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