A CONTRIBUTION TO THE SERVICE FAILURE OF LARGE CHILLED IRON ROLLS DUE TO FATIGUE

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October 15, 1952

ABSTRACT

A case of service rupture of chilled iron roll due to fatigue is presented with condition of rupture, investigation of the cause, and remedial result through remodelling.

As a result of this, it is suggested that service strength of chilled iron rolls should be considered through fatigue, and that standard size is not necessarily of sufficient strength from this point of view ; a remark for the prevention of service failures in existent mills, and to which reference is desired to make in building new mills.

1. Introduction

Rolls are vital part of rolling mills in respect both to efficiency and cost. In spite of modern development in design and fabrication service breaking of rolls is not so rare. Usually the cause is still vague, since such stresses as bending stress due to too high rolling pressure, thermal stress due to rapid heating or cooling, residual stress inherent from fabrication, etc., are mixed pellmell with insufficient strength or any of the flaws of the rolls. Increase of roll size raises the confusion.

As one of the main suppliers of rolls, especially of larger size, for metal industry in Japan, the authors' works has paid much attention to every possible failure of rolls, including season cracking, spalling, fire cracking, service ruptures due to thermal and bending stresses, etc.

Upon this, it happened incidentally a sequence of ruptures of chilled rolls in the plate mill shop of the authors' works. The authors who engaged in the investigation of the cause of this unexpected damage has made a suggestion in which a fatigue failure was proposed. The result of improvement based upon this prediction was turned to be true, and no rupture since the remodelling was produced in spite of slightly increased impact-giving behaviour of load.

Generally speaking further, up-to-date machine designs are progressively finding its basis upon the fatigue strength of the material used for the parts undergoing the reversal of stresses, and the older concept of "safety factor" needs to be strictly criticized and reanalysed. To this end, however, the results of ordinary fatigue tests for small polished specimens cannot be used directly, without modification. Nevertheless examples of actual fatigue failure with definite evidences are still scarce, for large size machine parts in particular.

In this paper the authors present a case of fatigue failure of chilled roll and made a criticism upon the strength of this kind of rolls from the view point of fatigue.

2. Roll Size and Condition of Rupture

The rolling mill is three-high plate mill of Lauth type, 7 feet in body length and driven by 1500 HP induction motor with fly wheel of capacity 14400 HP-s at rated revolution. The top and bottom rolls which are in question are of the size shown in Fig. 1 indicating the dimensions both before and after the remodelling.

Originally these rolls have been given a body length of 6 feet. Later, a more efficient production being urged, the length was increased to 7 feet, adding some 20 per cent rolling pressure with the other conditions unchanged. At the time, roll material was changed from chilled iron to alloy forged steel considering strength mainly. As well acknowledged generally however, the surface quality of finished plate being by all means inferior compared with that obtained by chilled rolls, use of chilled rolls was decided to put back.

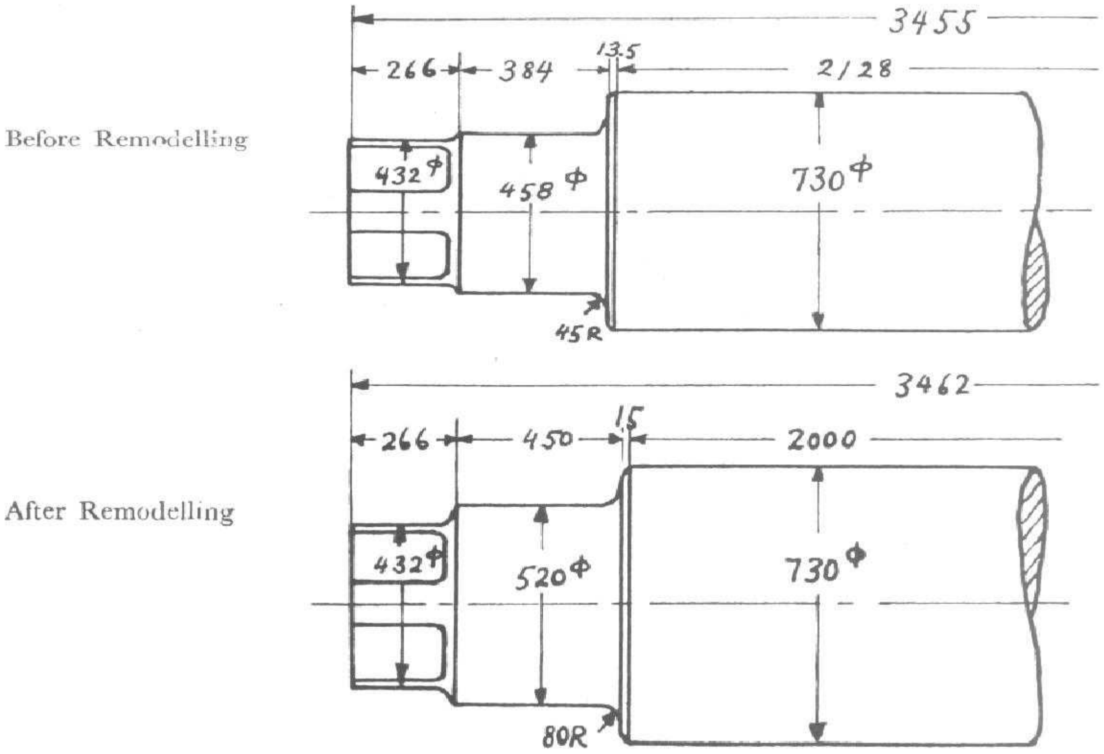


FIG. 1.—Roll dimensions before and after remodelling

In spite of much caution in operation, the new rolls were broken readily one after one as below.

Table 1. Rolling record of ruptured rolls—1

Rolls	Time of Rolling	Tonage Rolled	Total Revolution (1) with Rolling Pressure over 500 tons until Rupture
R 262	8h 55mn	85.8	3760
R 264	21h 5mn	221.9	4730
A—1002	4h 5mn	32.5	1120

(1) Cf. Table 4, P. 37

Ruptured portion is shown in Figs. 2 and 3.

It is seen in these figures that the ruptures started at the root of fillet and proceeded obliquely through the body, and that they differ from the one due to combined thermal and residual stresses which occurs perpendicularly to the axis in the middle portion of rolls.

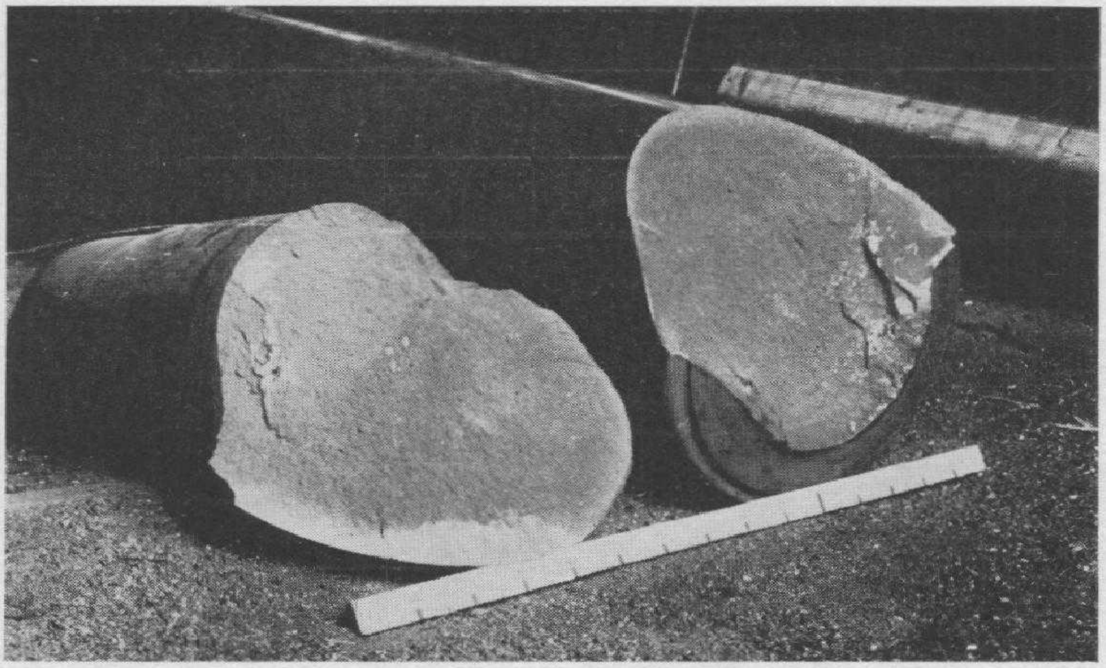


FIG. 2.—Photograph showing the surface of rupture

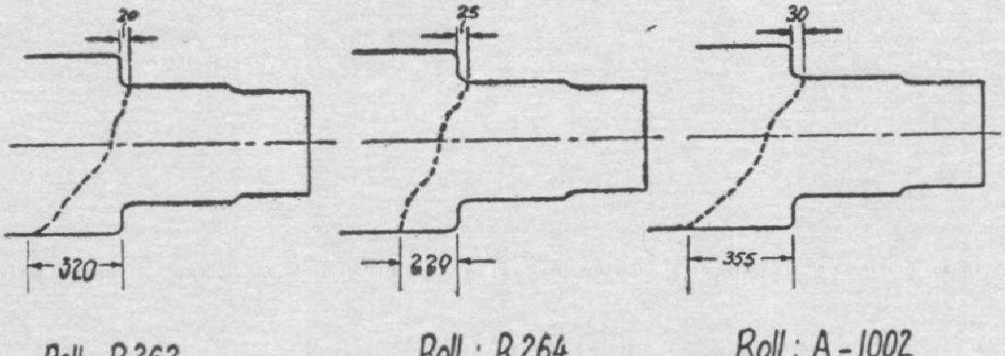


FIG. 3.—Position of rupture

Investigations with the ruptured rolls including chemical analyses (since these were order-made rolls at certain other maker's), microscopical examinations, hardness distribution tests along the radius or depth of chill, flaw inspection over the fracture surface, etc., revealed nothing abnormal as shown in Table 2, Figs. 4 and 5, and in Fig. 1 as well.

Table 2.——Chemical analyses of ruptured rolls.

Roll	Chemical Compositions						
	C	Si	Mn	P	S	Cu	As
R 262	3.06	0.59	0.22	0.480	0.046	0.08	0.101
R 264	2.76	0.59	0.26	0.500	0.054	0.10	0.101
A—1002	3.01	0.56	0.36	0.560	0.044	(Not Determined)	

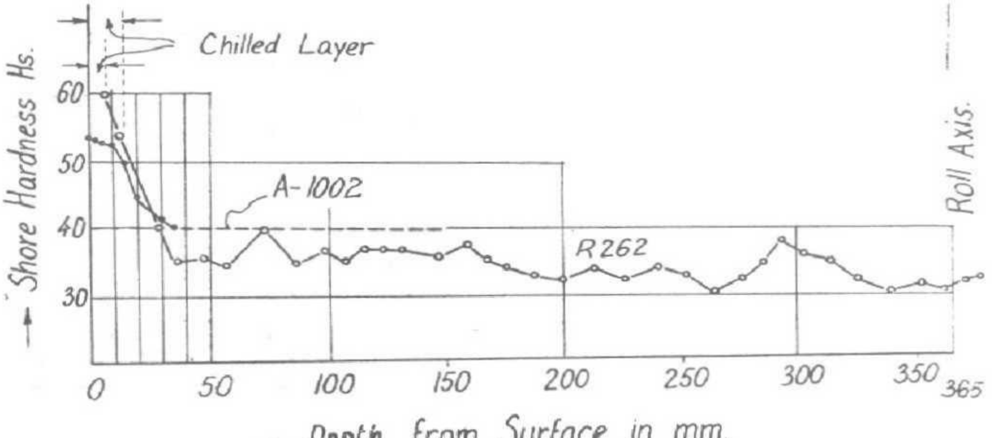
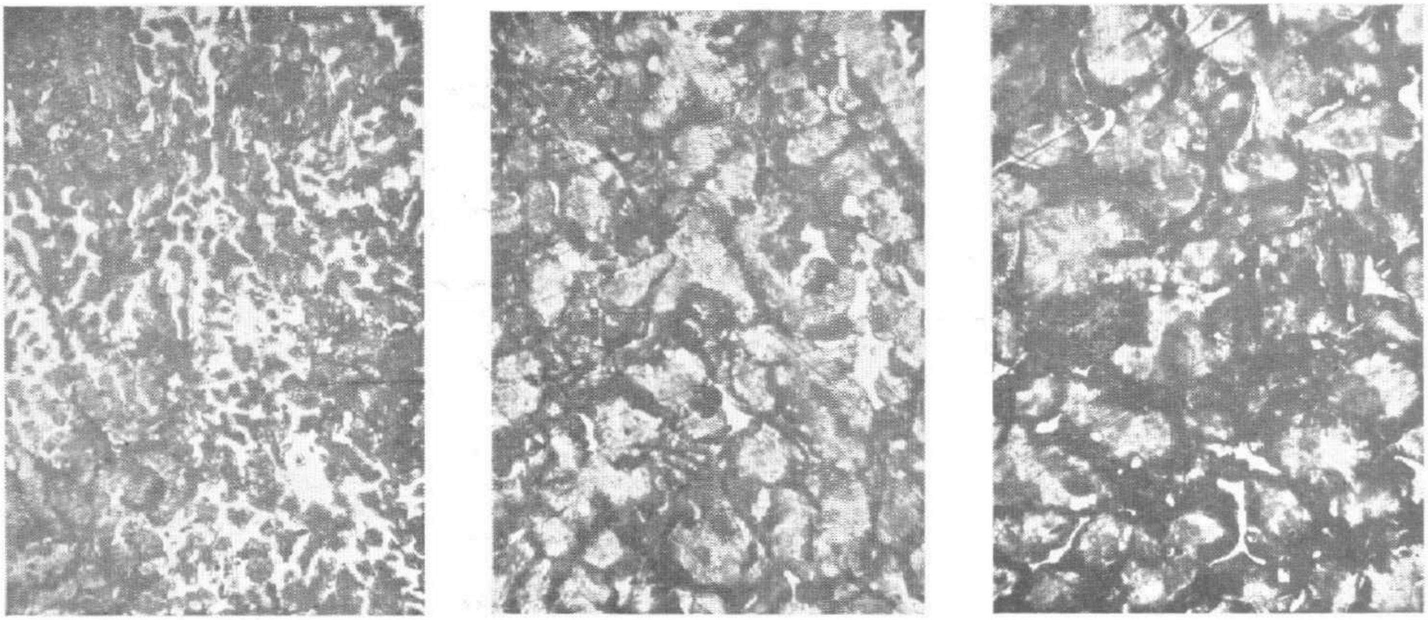


Fig 4


(a)
Outer Zone

(b)
Intermediate Zone

(c)
Core Zone

Fig. 5.—Photomicrographs of samples taken along the radius (roll: R262, × 50)

Thus roll neck strength was calculated with a speculation upon fatigue phenomenon in mind.

3. Evaluation of Fatigue Diagram for Roll Neck

3.1 Loading characteristics.

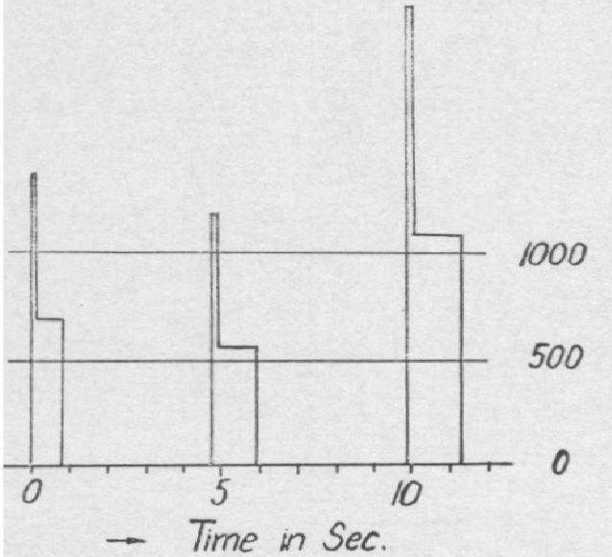


Fig 6

The rolling pressures vary from a pass to another during operation, and of course differ with the ingot or plate size. In certain single pass further, some impact can not be avoided at the "biting" point as shown in Fig. 6.

The plate mill is engaged for the most part in the production of 4.5 mm, 6mm, and 9mm plates. Then, if the standard rolling conditions are substituted into the Ekelund's formula*), total rolling pressures in each pass are obtained as shown in Fig. 7, 8, and 9 corresponding to 4.5 mm, 6 mm, and 9mm plates.

For the sake of simplicity, passes with total rolling pressure of some 500 tons or more were aken into account, and then, an average rolling pressure and a total revolution per plate were estimated over these passes as described in Table 3.

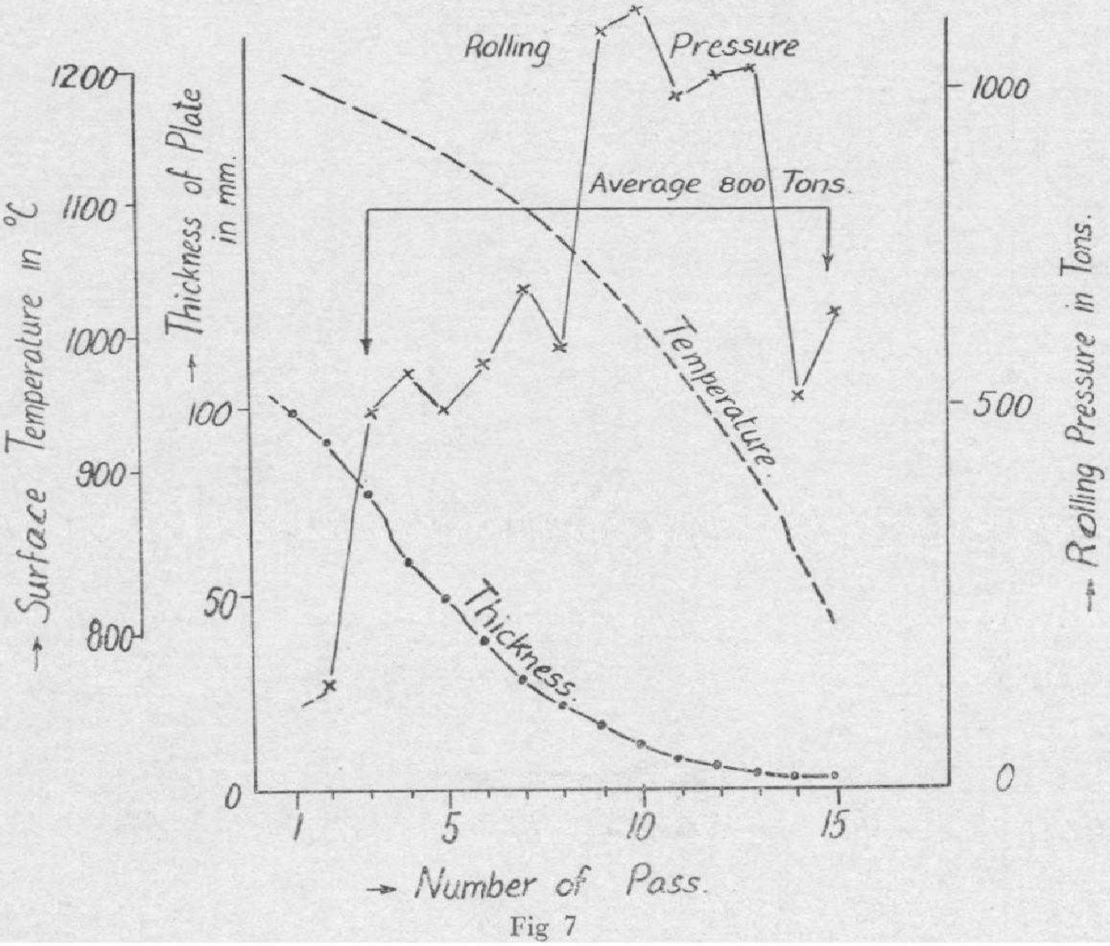


Fig 7

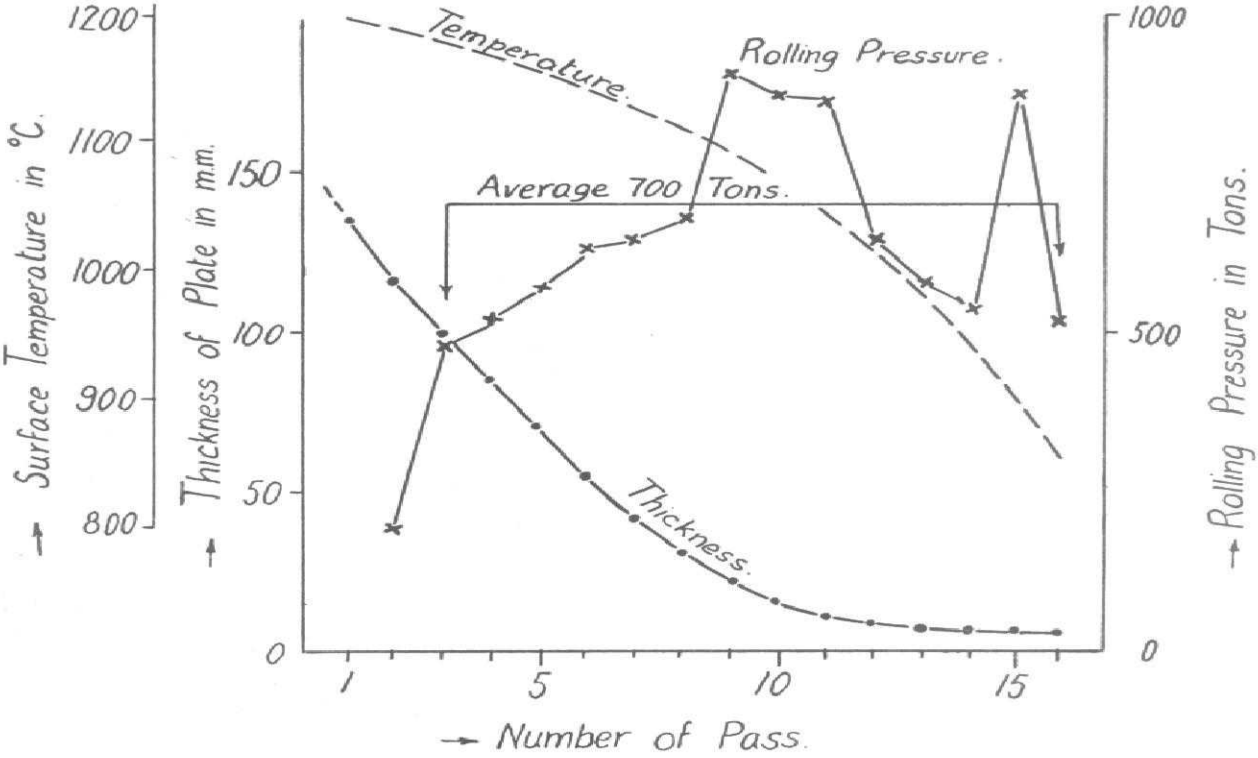

Surface Temperature in °C.
1200
1100
1000
900
800
Thickness of Plate in m.m.
150
100
50
0
Rolling Pressure in Tons.
1000
500
0
Temperature.
Rolling Pressure.
Average 700 Tons.
Thickness.
1
5
10
15
Number of Pass.

Fig 8

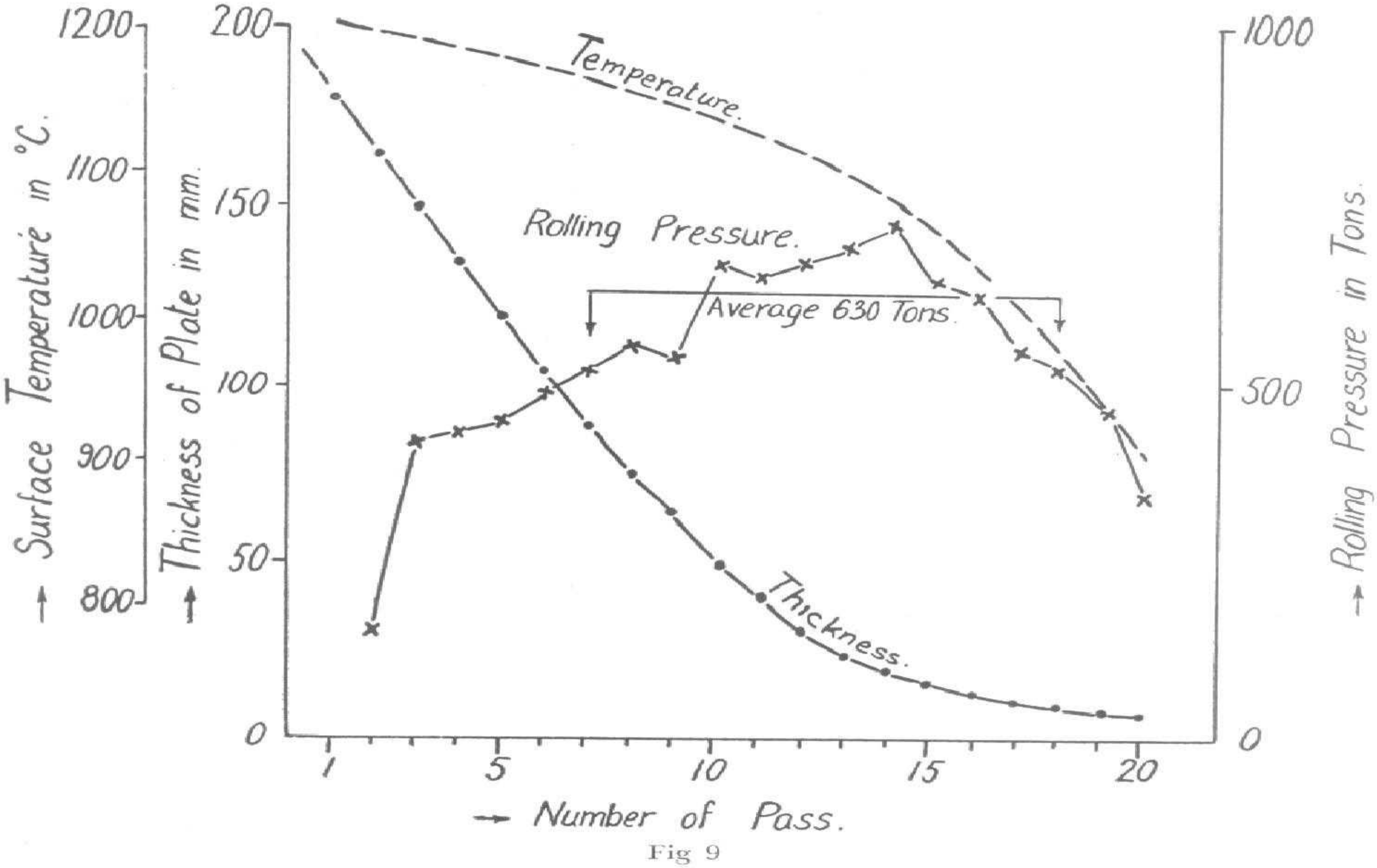

Surface Temperature in °C.
1200
1100
1000
900
800
Thickness of Plate in mm.
200
150
100
50
0
Rolling Pressure in Tons.
1000
500
0
Temperature.
Rolling Pressure.
Average 630 Tons.
Thickness.
1
5
10
15
20
Number of Pass.

Fig 9

Table 3.——Mean rolling pressure and total revolution per plate of several thicknesses.

Plate (1)	Mean Rolling Pressure	Total Revolution with Rolling Pressure over 500 tons per plate.
4.5 mm	800	16.7
6 mm	700	19.3
9 mm	630	15.6

(1) Extent of plate allows the finished plates to be cut in size of 5′×20′.

Classification of plates manufactured by the ruptured rolls are arranged in Table 4, in which total revolutions till rupture are also calculated.

Table 4.——Rolling records of ruptured rolls——II

Roll	Thickness and Number of Plates Rolled	Total Revolution with Rolling Pressure over 500 tons until Rupture
R 262	4.5 mm x 225 6 mm x 20 8 mm x 9 Total 254	16.7 x 225 (—254) =3760 (—4240)
R 264	9 mm x 303 and 12 mm, 15 mm, 19 mm etc. Total 345	15.6 x 303 (—345) =4730 (—5390)
A—1002	4.5 mm x 67 6 mm x 23 9 mm x 6 Total 96	16.7 x 67 (— 96) =1120 (—1605)

3.2 Calculation of Bending Stress

If we assume,

(i) Rolls are supported freely by reactions acting at the middle of necks.

(ii) Width of as-rolled blank is 1800 mm throughout the passes under discussion

as indicated in Fig. 10, bending moment at A of neck is for 4.5 mm plate.

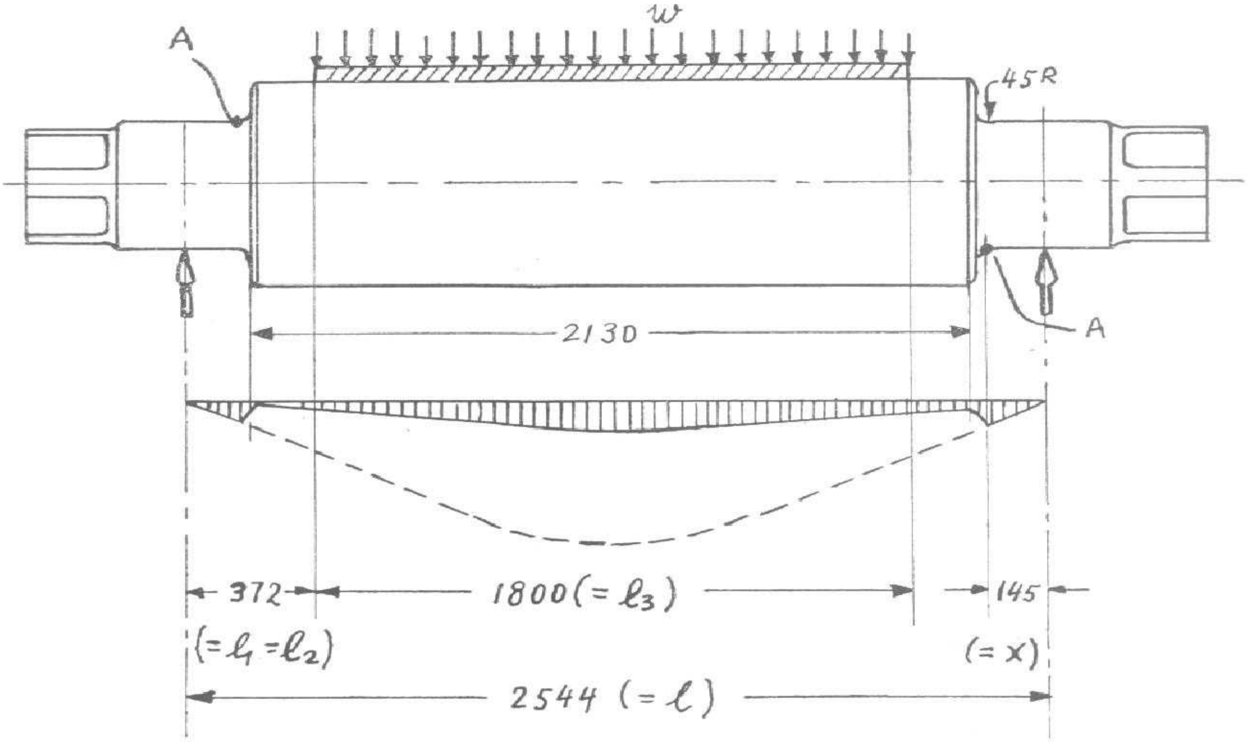


Fig. 10

$$M=\frac{W\,l_3}{l}\left(\ l_2+\frac{l_3}{2}\right)\times\ \ \frac{800}{2544}\cdot\times(372+\frac{1800}{2})\times 145$$

$$=58.1\ (\text{ton-m})$$

The section modulus of neck being

$$Z=938\text{x}10^4\ (\text{mm}^3)$$

Thence max. pure bending stress at A is

$$\sigma=\frac{58.1\ \text{x}\ 10^6}{938\ \text{x}\ 10^4}=6.15\ (\text{kg/mm}^2)$$

While, torque due to rolling pressure is (of. Fig. 11)

$$T=800\ \text{x}\ 0.028$$

$$=22.4\ (\text{ton-m})$$

Thus, denoting the equivalent bending moment based on the maximum principal stress theory by Me, the ratio Me/M is

$$\frac{Me}{M}=\frac{1+\sqrt{1+(T/M)^2}}{2}$$

$$=1.04$$

Therefore, is slightly enlarged to

$$=6.15\times1.04=6.40\ \ (\text{kg/mm}^2)$$

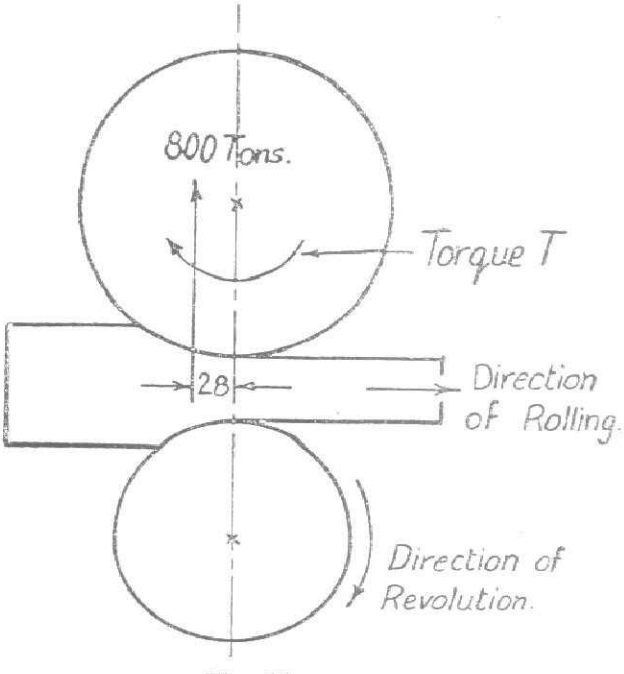


Fig. 11

3.3 S—N Curve for Roll Neck

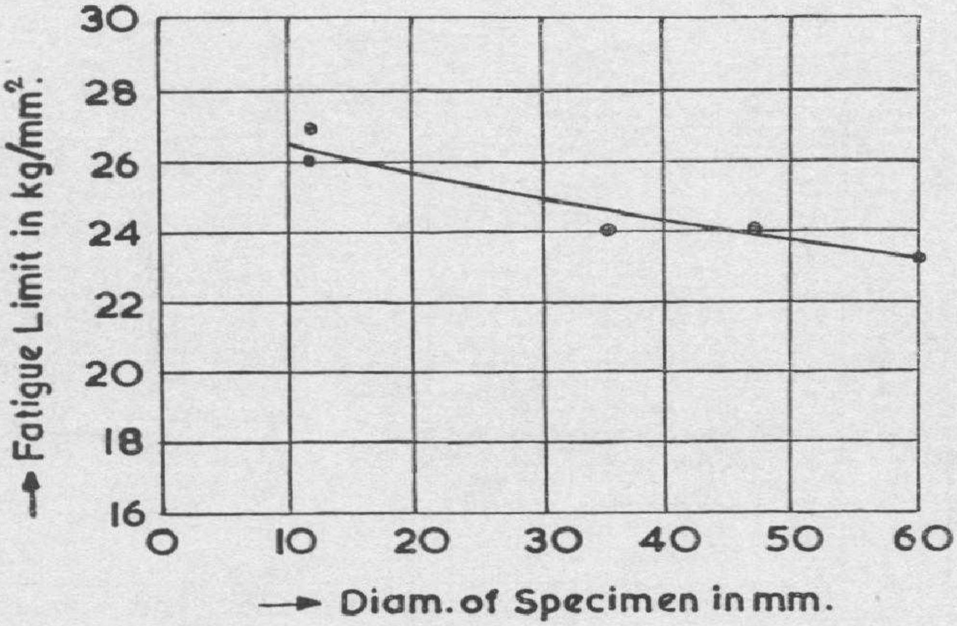


Fig. 12

We will now estimate the endurance limit of the roll neck from the data on rotating-beam fatigue tests of ordinary specimens about 10 mm in diam. Correlation of fatigue curve for actual roll neck to the rupture points will be interpreted in several ways. The authors followed a view in which the endurance limit of roll neck is lowered by the effects of size, fillet, etc. then that of ordinary specimens of grey cast iron. Lacking the data on cast iron specimens, moreover, those of carbon steels were considered as a basis of comparison.

Assumptions for the estimation of endurance limit for roll neck are as follows.

(i) Endurance limit of grey cast iron is 40 per cent of its tensile strength, 20 kg/mm², in the ordinary rotating-beam fatigue tests.

(ii) Although the size-effected decrease of endurance limit has been stated in various literatures, no definite conclusions are derived to date, as we see. Fig. 12 shows this effect by Dr. A. One , professor Emeritus of Tokyo University, in which maximum diameter of specimens does not exceed 60mm, a limit which corresponds to the maximum capacity of existing rotating-beam fatigue-test machine in Japan*).

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* See Appendix 2.

* Installed at the Yawata Iron and Steel.

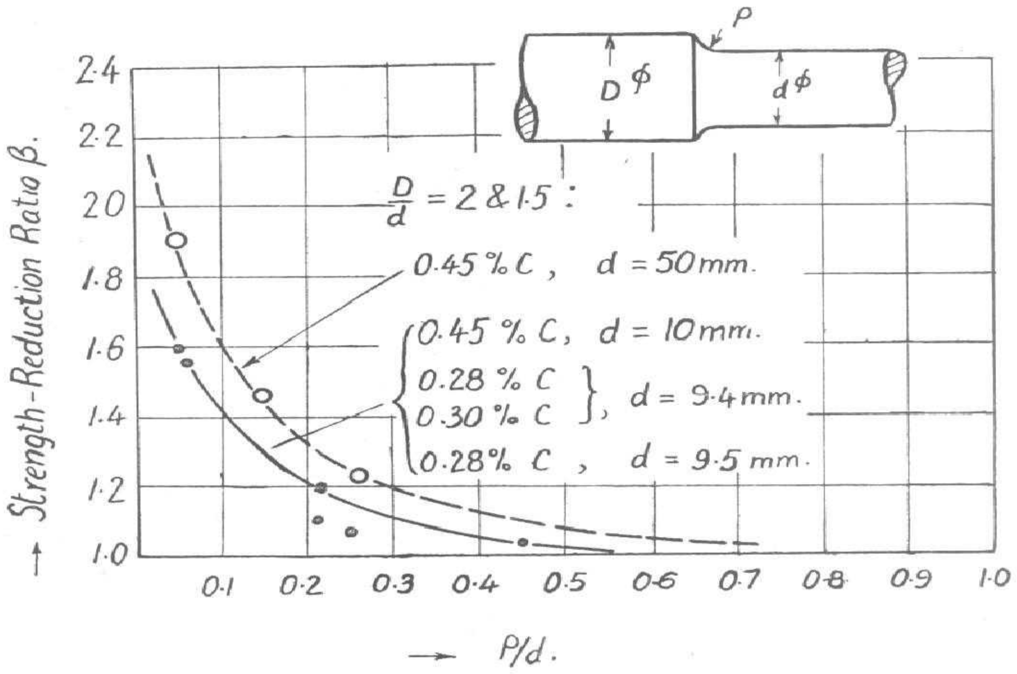

Fig. 13

According to this data, this effect is assumed to be 70 per cent with some extrapolation.

(iii) Effect of fillet radius is shown, for instance, as in Fig. 13 according to Mailander, Peterson, and others*). For cast iron the factor, that is strength-reduction ratio, is believed to fall off that of carbon steel. There is another opinion, however, that the expression

where $\beta \leq \alpha$

α : theoretical stress-concentration factor,

β : actual strength-reduction ratio.

does not necessarily hold for grey cast iron.

Thus we will assume $\beta = 1.4$

(iv) Effect of surface finishing grade might be neglected for such a porous material as cast-iron.

Then, the endurance limit of roll neck will be

$$\sigma_w = 20 \times 0.4 \times 0.7 \times \frac{1}{1.4} = 4.00 \text{ (kg/mm}^2\text{)}$$

Taking the knee point in the region of 10^6 revolution, the endurance curve at point A on roll neck becomes as shown in Fig. 14., in which the break points are also plotted. The slight shift downward of the endurance curve would be explained by the impact which is produced in

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* E. Lehr aud R. Mailander: Einfluss von Hohlkehlen an abgestutzten Wellen auf die Biegowechsel festigkeit, Z.V.D.I., Bd. 79, Nr. 33 (17 August 1935), S. 1005. R.E. Peterson and A.M. Wahl: Two-and-three dimensional cases of stress concentration and comparison with fatigue tests, J. Appl. Mech., Vol. 3, No. 1 (March, 1936), A—15.

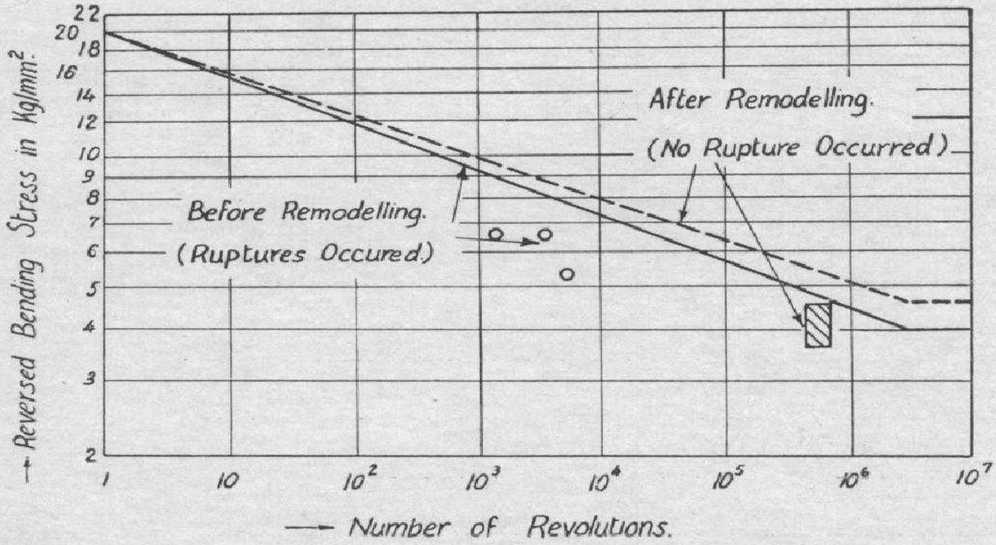

Fig 14

the "biting" period of each pass as already shown in Fig. 6, though the time of impact is supposed to be as short as from 1 to 1.5 sixtyth of one revolution.

4. Remodelling and Results Thereafter

Thus far, the authors predicted those breaks to be resulted by fatigue due to lack of strength. Remodelling was carried out, in which the diameter of neck and fillet radius were raised to a size as permissible as large by the existent roll stand as already shown in Fig. 1, and through which also. The bending stress at roll neck was reduced by about 30 per cent, raising the endurance limit to 4.7 kg mm² as well.

The result was entirely satisfactory. To date, already rolled from 10000 to 14000 tons after remodelling (Table 5), no break was seen inspite of the increased impact by raising roll speed from 50 to 70 r.p.m. during this period.

Table 5.——Rolling record after remodelling.

Roll Number	1	2	3	4
Tonage Rolled, (1) tons	14000	12150	10700	10270
Time of Rolling, hr	825	728	639	677
Reduction of Diam. Ground. mm	16	12	10	11
Present Surface Hardness, Hs	57—54	57—54	57—54	57—54

(1) Figure per pair of top and bottom rolls.

5. CONSIDERATION

Though the break points fall closely to the estimated endurance curve as stated in the previous section, the assumptions made were in generous side. If these, especially effect of size and ratio of endurance limit to tensile strength, are taken more severely, the coincidence will be better.

Turning our eyes to other makers' mill in Japan, next, two tables might be provided for reference. First, Table 6 shows chief dimensions of the rolls of similar body size in Japan including the standard size unified by the Iron & Steel Institute of Japan, from which it will be seen that roll neck size of the authors' works has been too small. Second, in Table 7 two cases of prevention of service failure are provided.

Table 7.——Two cases of similar remodelling in Japan.

Name of Company		A	B
Neck diam.	Before Remodelling	450	..
	After ,,	490	..
Fillet Radius	Before Remodelling	80	65
	After ,,	85	80
Total Estimated Roduction in Stress %		25	7

Table. 6—Chief dimensions of roils installed at representative works in Japan.

Name of Company	Body			Neck			
	D(mm)	L(mm)	L/D	d(mm)	d/D	l(mm)	R(mm)
Osaka Seiko (Osaka Steel Works)	735	2000	2.72	533	0.725	370	90
Azuma Seiko (Azuma Steel Works)	720	2100	2.92	490	0.680	385	85
Nakayama Seiko (Nakayama Steel Works)	720	2000	2.78	550	0.765	380	65
Amagasaki Seiko (Amagasaki Steel Works)	720	2000	2.78	520	0.723	440	65
Nippon Kokan (Nippon Steel Tube Co).	700	2100	3.00	520	0.743	400	85
Tokai Kogyo (Tokai Steel Works)	700	1900	2.72	480	0.685	385	85
Yawata Seitetsu (Yawata Iron and Steel Works)	650	1800	2.77	440	0.677	365	30
Standard Size	730	2000	2.74	530	0.730	450	80

Japan Steel Works	Before Remodelling	730	2130	2.92	458	0.628	395	45
	After Remodelling	730	2000	2.74	520	0.712	450	80

Roll strength should not be argued, of course, regardless to power used by mill which increases with diam, of rolls, and to the reduction in operation.

However, if the life of chilled roll is assumed to be 20000 tons, the corresponding total revolution nears that of knee point. While the statical bending stress meant above is still large even with the standard size, keeping the ratio of endurance limit to the statical strses at 1.0—1.3.

Thence, with additional consideration of both impact behaviour of load and possible residual stress, breaking of chilled rolls without any flaw is not impossible, when sufficient precautions are not taken in works operations. Thus strength of chilled rolls needs to be reexamined for both existing and new mills, not forgetting the draft arrangement in operation.

6. Summary and Conclusions

An example of rupture of chilled iron roll due to fatigue in the author's works was presented with condition of rupture, investigation of the cause, and remedial result through remodelling.

As a result of this case, it is suggested that service strength of chilled iron rolls should be considered through fatigue, and that standard size (in Japan) in Table 6 is not necessarily of sufficient strength from this point of view.

In concluding this paper, the authors express their cordial thanks to the directors of the Japan Steel Works Co. Ltd. for the permission of publishing this paper.

Appendix I.

Ekelund's formula.

$$P = bm\sqrt{R\,(h_1 - h_2)}\left\{1 + \frac{1.6\mu\sqrt{R\,(h_1-h_2)} - 1.2\,(h_1-h_2)}{h_1+h_2}\right\}\left\{T + \frac{2\xi v\sqrt{(h_1-h_2)/R}}{h_1+h_2}\right\}$$

Where

P=total rolling pressure in kg.,

μ=coefficient of friction$=1.05-0.0005t$.,

ε=ductility constant in kg-sec/mm^2$=0.01(14\text{-}0.01t)$,

bm=average width of blank in mm.,

R=radius of roll body in mm.,

for Lauth type mill.,

$$R = \frac{2R_1\,R_2}{R_1+R_2}$$

where R_1 and R_2 are radii of top and bottom, and middle rolls respectively.

h_1=height of blank before entry in mm.,

h_2= ,, ,, ,, after exit in mm.,

v=peripheral speed at roll surface in mm/s,

T=compressive strength of steel in kg/mm^2

$=(14\text{-}0.01t)\;(1.4+C+Mn)$

C: percent of carbon,

Mn: ,, manganese,

t—rolling temperature in °C.

Though this formula debuted about 20 years ago in English literature, it is still used with sufficiently practical reliability (Cf., Iron & Steel, Dec., 1950, p. 481).

Appendix 2.

In considering the endurance diagram of actual roll neck based upon the data of small specimens, either of the following courses might be traced.

(*i*) Simple bending stress of actual smooth neck is calculated and the endurance limit of small specimen is lowered by the effects of size, fillets, etc. (Cf. Fig. 15).

(*ii*) Simple bending stress of smooth neck is multiplied by the strength-reducing ratio of fillet, reciprocal of the size factor, etc., while the endurance limit of small specimen unchanged.

(*iii*) Intermediate courses of (*i*) and (*ii*), in respect to the treatment of effects of size, fillet, etc.