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Mathematical expression for hot-rolling loads as a function of steel composition and temperature

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Although plain carbon steels are produced commercially, few studies seem to attempt to develop a mathematical model for applications in computer-controlled mills. An expression is proposed to calculate hot-rolling loads while rolling in austenitic regions (800–1100 °C) giving a 30% reduction in each pass.

$$L/W = (6 - 37\times10^{-4}T) + [(7.9 - 73\times10^{-4}T)\times C] + [(5.2 - 51\times10^{-4}T)\times Si]$$

where L/W – rolling load per unit width (kN/mm)
T – mean hot rolling temperature (°C)
C and Si – carbon and silicon in steel (wt%)

Among common alloying elements, carbon content had a more significant effect on rolling loads than silicon content, and the amount of manganese had practically no effect hence, it is not incorporated in the proposed equation.

1. Introduction
During hot rolling, strain hardening and softening occur simultaneously due to favourable dislocation movements, especially by cross slip and diffusion climbing. The structural changes taking place within the material result in an increased dislocation density with strain and consequently a higher rolling load is needed if the material is worked further without full recovery and recrystallization. Recovery and recrystallization are time dependent and their rates may depend substantially on such factors as the working temperature, the amount of deformation, the cooling rate, the stacking-fault energy and the composition.

The production of plain carbon steel by modern rolling mills continues unabated based on several years of experience and basic studies. The effect of common alloying elements (e.g. carbon, silicon or manganese) in plain carbon steels on rolling loads, while working above 800 °C ($>0.5T_m$), does not seem to have been studied systematically. This paper observes the effect of the hot-working temperature and common alloying elements, while giving a known deformation, on rolling load. A mathematical expression has been proposed, using these observations, for calculating the hot-rolling load.

2. Experimental procedure
2.1. Steel analysis
An analysis of the steel bars used in this study is given in Table I. Fifteen steel compositions were selected to give the following ranges, 0.04–0.50 wt % carbon 0.02–0.42 wt % silicon, and 0.02–1.22 wt % manganese. Sulphur and phosphorus were below 0.04 wt % in all steels. The steel bars had a 15 × 30 mm section obtained by an extrusion process.

2.2. Rolling equipment
Two high (Hille-50) rolling mills having 500 kN rolling load capacities was used in this work. The rolling load was recorded on a UV chart recorder, and the temperature of the steel sample was recorded continuously on a strip-chart recorder from soaking, to the rolling period, and until cooling.

2.3. Rolling procedure
The extruded bars were cut into 130 mm long, pieces for rolling purposes. These were sand blasted to remove glass lubricant. The thickness and width of the bar was noted. A Pyrotenax-mineral-coated alumel/chromel thermocouple was fixed in the middle of the bars so that the thermocouple tip was nearly at the centre. The steel bars fitted with thermocouples were kept in the furnace (with a protective atmosphere) and maintained at a predetermined reheating temperature for 30 min. After reheating, the bar was rolled at a predetermined temperature giving a 30% reduction in one pass. A typical temperature profile during rolling with a three-pass design is shown in

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TABLE I Chemical Analysis of Steel

Sample number	Steel code	Chemical composition (wt %)				
		C	Si	Mn	S	P
1	A	0.04	0.31	0.88	0.040	0.041
2	B	0.08	0.38	0.91	0.030	0.022
3	C	0.07	0.12	0.34	0.023	0.030
4	D	0.04	0.12	0.51	0.035	0.044
5	E	0.07	0.24	0.41	0.017	0.036
6	F	0.50	0.40	0.92	0.022	0.044
7	G	0.11	0.44	0.09	0.040	0.049
8	H	0.17	0.38	0.99	0.025	0.037
9	I	0.18	0.29	0.53	0.029	0.043
10	J	0.24	0.41	0.91	0.014	0.039
11	K	0.23	0.27	1.22	0.012	0.031
12	M	0.25	0.18	0.49	0.027	0.038
13	N	0.17	0.34	0.96	0.030	0.040
14	P	0.18	0.14	0.18	0.016	0.041
15	Q	0.03	0.02	0.08	0.010	0.025

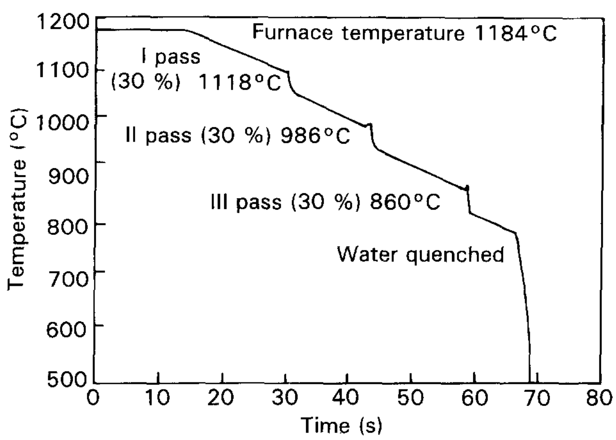

Figure 1 A typical temperature profile during three pass-rolling.

Fig. 1. The thickness and width of the specimens were noted after cooling.

2.4. Determination of load/width and flow-stress values

During three-pass rolling only the initial and final values of thickness and width of the slab could be measured; hence, for the intermediate stages of rolling, the thickness and width had to be estimated. The thickness of the rolled material during intermediate passes was estimated by adding the roll-deflection values to the adjusted roll gap. These roll-deflection values were obtained during single-pass rolling in a particular mill. The width spread was determined as approximately 6.48%, 12.47% and 16.47% in the first, second and third pass, respectively, with a 30% reduction in each pass.

The rolling load per unit width (L/W) was calculated after the width, W was measured or estimated and the rolling load, L, was known from the UV chart recording. The flow stress, $\bar{\sigma}$ is given by Sim's equation [1].

$$\bar{\sigma} = \frac{(L/W)}{(R\Delta h)^{1/2}Q} \qquad (1)$$

where R is the roll radius (68.8 mm), Δh is the change in thickness during rolling (mm) and

$$Q = \left[\left(\frac{h_f}{4(h_0 - h_f)}\right)^{1/2}\left\{\pi \tan^{-1}\frac{(h_0 - h_f)^{1/2}}{h_f} - \left(\frac{R}{h_f}\right)^{1/2}\log_e\left(\frac{h_t}{h_0 h_f}\right)\right\} - \frac{\pi}{4}\right]$$

h_0, h_f, h_t are the thicknesses initially, finally and at the throat of the roll. The proportional values of Q for a particular R/h_f was noted [1] for 30% reduction. Substituting the values of L/W, R, Δh and Q in Equation 1, the flow-stress values were calculated and they are given in Table II.

3. Results and discussion

In order to ensure the reproducibility of the rolling-mill data, two samples (steel H and M) were rolled on two different dates giving a rolling-load difference less than 4% which was within experimental limits.

The steels D, F and K were given three passes (each of a 30% reduction) at temperatures of 1100, 990 and 860 °C. The L/W values linearly increased with decreasing rolling temperatures. However, it was noted that at 860 °C the L/W values increased with carbon content assuming that other elements are of negligible influence. Following this observation, the other steel samples B, G, H, J, M and N were also rolled in an identical manner and L/W values were plotted against temperature revealing a scatter of data at 860 °C for increasing C, Si and Mn contents. Of these three alloying elements in steel, carbon appeared to be most effective, being an interstitial element, whereas silicon had relatively less effect as shown in Fig. 2. Manganese, however, does not seem to affect the rolling load dependence on temperature. The L/W values appeared to vary linearly with composition and temperature.

To evaluate the combined effect of C, Si and Mn on L/W values in the austenitic temperature range (860–1100 °C) a relation

$$L/W = U + (V \times C) + (W \times S) + (Z \times M) \qquad (2)$$

was assumed since all the elements exhibited a linear relationship, where U, V, W and Z are temperature-independent constants and C, S and M are the carbon, silicon and manganese weight percentages in steel. A multiple regression of the L/W values with the three variables C, S and M for particular rolling temperatures. 3 T(°C) yielded the values of the constants U, V, W and Z. Since three rolling temperatures were used and the three constants have a linear temperature relationship, the values of U, V, W and Z were substituted in Equation 2, in terms of temperatures, as giving

$$\begin{aligned} L/W = {} & (6 - 37 \times 10^{-4}T) \\ & + [(7.9 - 73 \times 10^{-4}T) \times C] \\ & + [(5.2 - 51 \times 10^{-4}T) \times S] \qquad (3) \end{aligned}$$

The term for manganese in Equation 3 was not incorporated since the value of its mutiplier, Z, was very small. Equation 3 was used to calculate the rolling load for steels A, E, I, O, P and Q. The calculated and experimental values of L/W thus obtained are given in Table III. It was found that the two values differed, with the error ranging from + 7.8% to − 25.8% and the mean error was − 8.2% for 17 observations. Realising that this error is on the high side, a check was made on the most significant factor, the rolling temperature.

A magnified view, Fig. 3, of the temperature recording for rolling, shown in Fig. 1 revealed that the temperature of a sample increases by about 5 °C due to friction while entering in the rolls at the rolling-in temperature. When the sample is enveloped by rolls it experiences chill, its temperature drops by about 30–40 °C, and the steel emerges from rolls at a lower rolling-out temperature. This temperature drop is plotted against the rolling-in temperature in Fig. 4 which shows that the magnitude of the drop in temperature increases with the rolling-in temperature. The average of the rolling-in and rolling-out temperatures is the mean-rolling temperature. Recalculated L/W values using the mean-rolling temperature in Equation 3 are given in Table IV; this considerably decreases the difference between the calculated and experimental values. The error values now range between + 2.6 to − 16.6% with a mean error of − 2.9%, which could be an acceptable limit. Equation 3 was used by Kharadkar [2] when studying the effect of rolling temperature and steel composition on rolling load using a similar rolling mill and experimental procedure.

The values calculated by Kharadkar for L/W using Equation 3 and the experimental values obtained by Kharadkar are given in Table V which shows very good agreement.

The equation to calculate hot-rolling load testifies to a few known facts. The increased working temperature renders dislocation movement easy, giving a lower rolling load. In addition to temperature factors, increased quantities of alloying elements (e.g. carbon and silicon in solid solution) render the austenite less ductile and it requires a higher load while rolling. The effect due to carbon is more pronounced because of its

TABLE II Experimental values of L/W and $\bar{\sigma}$ at different rolling temperatures

Sample number	Steel code	Composition (wt %)			1100 °C		990 °C		860 °C	
		C	Si	Mn	L/W (kN mm^{-1})	$\bar{\sigma}$ (MPa)	L/W (kN mm^{-1})	$\bar{\sigma}$ (MPa)	L/W (kN mm^{-1})	$\bar{\sigma}$ (MPa)
1	D	0.04	0.12	0.51	2.03	114.8	2.67	148.1	2.82	187.6
2	B	0.083	0.38	0.91	1.67	92.7	2.96	147.0	3.54	211.2
3	G	0.11	0.44	0.91	1.67	92.1	2.48	139.0	3.00	194.5
4	H	0.17	0.38	0.99	1.89	97.9	2.62	159.6	3.67	232.5
5	N	0.17	0.34	0.98	1.89	102.0	2.89	155.3	3.48	218.3
6	K	0.23	0.27	1.22	1.88	106.9	2.68	158.3	3.33	219.1
7	J	0.24	0.49	0.92	1.97	116.1	2.97	171.6	3.68	238.2
8	M	0.25	0.18	0.49	1.96	108.7	2.75	158.2	3.39	216.5
9	F	0.50	0.40	0.92	1.82	91.0	2.55	158.8	3.80	240.8

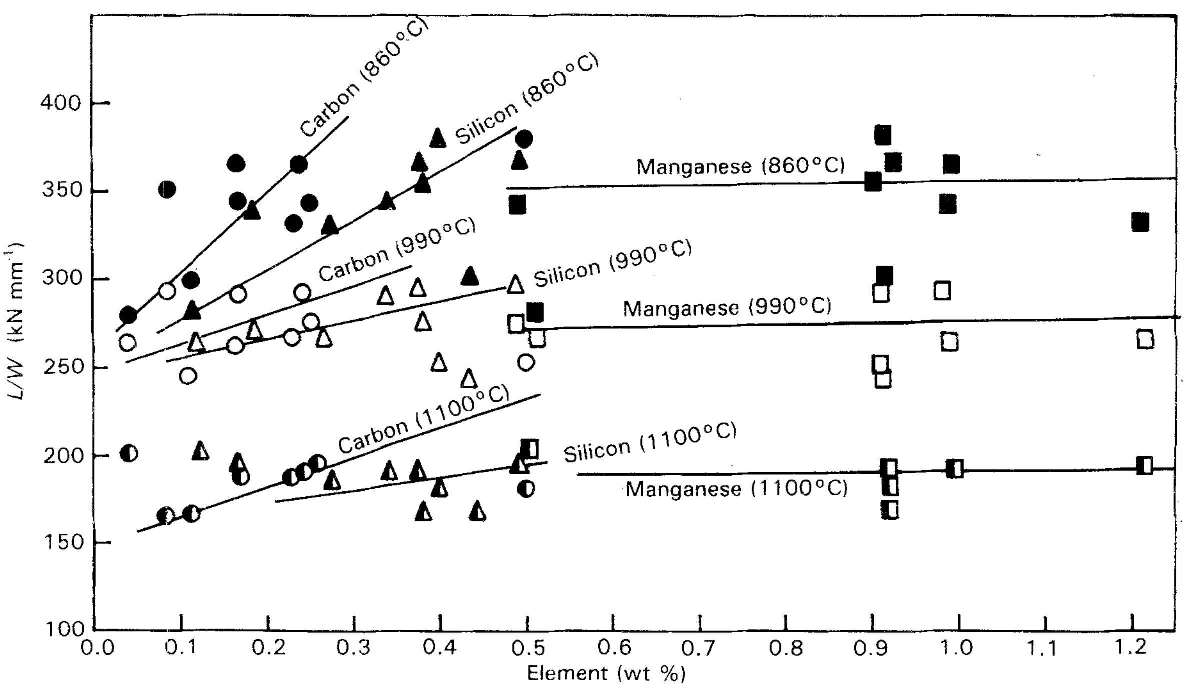

Figure 2 Effect of alloying elements on rolling load at different temperatures.

TABLE III Verification of Equation 3 using the rolling-in temperature; in each case the rolling schedule was a 30% reduction on each of three passes

Sample number	Steel code	Composition (wt %) C	Si	Mn	Rolling-in temperature (°C)	Rolling load (kN mm^{-1}) L/W Calculated L_c	Experimental L_e	$100(L_c - L_e)/L_c$ Error (%)
1	A	0.04	0.31	0.88	1125	1.65	1.75	– 6.06
					1003	2.34	2.44	– 4.27
					860	3.14	3.24	– 3.18
2	E	0.07	0.24	0.41	1100	1.82	1.88	– 3.29
					985	2.44	2.68	– 9.80
					906	2.87	3.20	– 11.49
3	I	0.18	0.29	0.53	1154	1.43	1.80	– 25.08
					990	2.50	2.73	– 9.02
					860	3.34	3.56	– 6.05
4	O	0.05	0.42	0.29	1100	–	–	–
					990	2.43	3.02	– 24.02
					860	3.24	3.25	– 0.3
5	P	0.18	0.14	0.18	1100	1.84	2.03	– 10.03
					990	2.47	2.75	– 11.03
					860	3.22	3.52	– 9.03
6	Q	0.03	0.02	0.08	1100	1.91	1.76	– 7.08
					990	2.36	2.70	– 14.04
					860	2.88	2.78	– 3.04

TABLE IV Verification of Equation 3 using mean-rolling temperature

Sample number	Steel code	Steel composition (wt %) C	Si	Mn	Rolling temperature (°C) In	Out	Mean	Rolling load (kN mm^{-1}) L/W Calculated L_c	Experimental L_e	Error (%) $100(L_c - L_e)/L_c$
1	A	0.04	0.31	0.88	1100	1074	1087	1.87	1.85	1.06
					984	946	965	2.55	2.73	– 7.0
					860	834	847	3.21	3.20	– 0.3
2	E	0.07	0.24	0.41	1100	1049	1075	1.95	1.88	– 3.5
					985	935	960	2.58	2.68	– 3.8
					906	860	883	3.00	3.20	– 6.6
3	I	0.18	0.29	0.53	1154	1100	1127	1.61	1.80	– 11.8
					990	946	968	2.64	2.73	– 3.4
					860	822	841	3.46	3.56	– 2.9
4	O	0.05	0.42	0.29	990	937	964	2.59	3.02	– 16.6
					860	827	844	3.34	3.25	– 2.6
5	P	0.18	0.14	0.18	1100	1058	1079	1.96	2.03	– 3.5
					990	940	965	2.62	2.75	– 4.9
					860	818	839	3.34	3.52	– 5.3
6	Q	0.03	0.02	0.08	1100	1051	1076	2.01	1.76	– 12.4
					990	937	964	2.46	2.70	– 9.7
					860	839	850	2.92	2.78	– 4.7

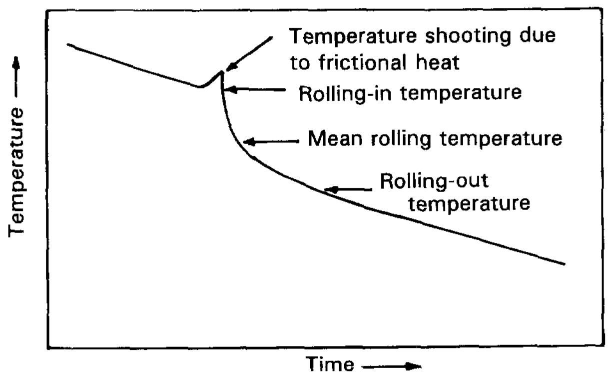

Figure 3 Schematic temperature profile during hot rolling showing a rise and drop in temperature.

interstitial alloying behaviour. The effect of manganese on the ductility of austenite is less pronounced since it is an austenite stabiliser; hence, this factor has been omitted from Equation 3.

4. Conclusion

From the observations, the rolling load (kN mm^{-1}) during hot rolling (800–1100 °C) of plain carbon steel (C and Si up to 0.5%, Mn up to 1%) can be expressed by the following equation for a 30% reduction

$$L/W = (6 - 37\times10^{-4}T) + [(7.9 - 73\times10^{-4}T) \times C] + [(5.2 - 51\times10^{-4}T)\times S]$$

TABLE V A comparison of the calculated load and the observed rolling-load values, by Kharadkar [2]

Sample number	Steel Composition			Temperature (°C)		Rolling load, L/W (kN mm^{-1})		Error (%)
	C	Si	Mn	Rolling-in	Mean rolling	Calculated L_c	Observed L_e	$100\frac{(L_c - L_e)}{L_c}$
1	0.23	0.15	0.49	850	830	3.49	3.60	− 3.0
2	0.13	0.93	1.03	950	929	3.13	3.08	− 1.5
3	0.23	0.15	0.45	950	929	2.88	2.56	− 11.0
4	0.59	1.4	0.84	950	929	3.87	3.98	− 3.0
5	0.21	0.32	0.63	950	929	2.94	3.11	− 5.7
6	0.23	0.15	0.49	1000	977	2.59	2.13	− 17.0
7	0.23	0.15	0.49	1050	1025	2.29	2.03	− 11.0

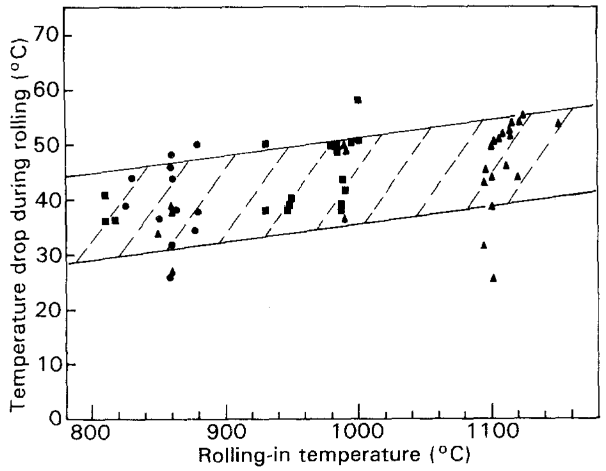

Figure 4 Temperature drop during rolling due to chilling by rolls, for sections: (▲) 15 × 30 mm, (■) 10.5 × 31 mm, and (●) 7.3 × 33 mm.

where T is the mean hot-rolling temperature (°C) and C and S are the carbon and silicon weight percentages in steel. This equation is expected to give the rolling load within an accuracy of ± 10%.

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