THE EFFICIENCY OF ROLL TRAINS.

By Wm. Hewitt, M.E.

General Remarks.—The efficiency of any machine is the fraction of the whole amount of power communicated to it, which may be usefully developed, or the ratio of the useful work executed to the total work performed. When the efficiency is unity, the machine is perfect; that is, it is capable of transmitting the whole amount of power communicated to it. No machine can be perfect, because it is impossible to construct one that will be entirely free from friction. In every machine, more or less power is always absorbed in overcoming this element. The fewer the parts, the less the amount of friction, and, therefore, assuming all other things to be equal, the simpler the machine, the greater its efficiency; hence also the common adage, "simplicity is perfection." But simplicity alone is not sufficient for a large efficiency. Unless the machine is constructed upon correct principles, its simplicity is of no avail. The rectitude of such principles consists in their strict accordance with all the laws of nature. It is useless and foolish to contend against these laws, for, unlike those of our legislative bodies, they will inevitably be enforced. We cannot but pity those unfortunate persons, who, in ignorance of nature's laws, are struggling blindly against them, mistaking their pertinacity for genius, and flattering themselves that they are inventors. And equally must we pity those, who, in search of the so-called perpetual motion, are wasting their time and energy in a hopeless cause, deceiving themselves with the idea that they can create power. He who would devise a machine should understand that a machine should be constructed with regard to obtaining as large an efficiency as possible, and not merely a piece of mechanism. He should, therefore, be instructed in the principles which govern the efficiency of machines, and consequently be intimately acquainted with the laws of nature, for the more strictly he adheres to these, the more completely will he gain the merit of simplicity.

The Rolls.—The determination of the efficiency of roll trains involves the determination of the normal pressure exerted upon the rolls by the hot bar or plate while under compression. The brasses act as brakes on the journals of the rolls, and if the normal pressure be denoted by P, and the coefficient of friction by f, the resistance will be given by the equation,

$$R=\frac{P}{f}. \tag{1.}$$

The value of P, for each passage of the iron between the rolls, depends upon the amount of reduction produced in the sectional area of the bar or plate. We should seek to make the resistance of the train as nearly uniform as possible, and in order that this may be effected, it is evident that the rate of reduction must be varied according to some function of the variation of the temperature, and the position of the metal in the train. The resistance which iron at different temperatures offers to compression has never been accurately determined; but the diminution of the tensile strength of wrought iron, below the maximum for high degrees of heat, was determined by a committee appointed by the Franklin Institute to investigate the principles relating to the strength of materials for boiler construction, and found to be given by the empirical formula,

$$D=C(\theta-80)^{2.6}, \tag{2.}$$

in which D is the diminution after it has passed the maximum, θ, the temperature, Fah., and C, a constant. This formula is sufficiently exact for all temperatures between 520° and 13·7° (JOUR. FRANKLIN INSTITUTE, Vol. 20, 1837). The resistance of iron to compression is about equal to its tensile resistance, and the above formula, therefore, may be applied to the case under consideration, with approximately correct results being obtained.

In using this formula, let R' denote the amount of reduction in the first pass, found by experiment to be most advantageous for the temperature of the pile, a_1, the increase of resistance from the first to the second pass, a_2, the increase from the second to the third, etc. The successive reductions then become, R' for the first pass, a_1R' for the second, a_1a_2R' for the third, and $a_1a_2 \ldots a_nR'$ for the nth pass.

The temperature of the iron, however, is a very difficult thing to obtain accurately, and the method usually employed, is to adopt a rate of reduction which is most favorable to the mean temperature of the iron and the size of the rolls; to calculate the number of passes on the assumption that this rate is constant, and then to depart from this in the various grooves, as may seem most discreet. This requires considerable experience, especially in rolling wire rods, where the cooling is very rapid. In rolling rails, beams, and plates, however, the problem is not such a delicate one, as the iron cools more slowly.

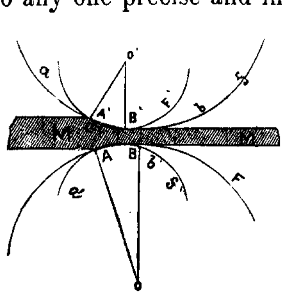
The most rapid and convenient method of calculating the areas of the various grooves is by the use of logarithms. Thus, let the number of grooves be denoted by n, the rate of reduction (assuming it to be constant) by r, and the area of the last groove by a. Then,

Log. of area of pass $n = \log. a$.

" " " $(n - 1) = \log. a + \log r$.

" " " $(n - 2) = \log. a + 2 \log. r$, etc.

The rate of reduction also depends upon the character of the iron, the dimensions and compositions of the pile, the alterations which the iron experiences in its shape, and the size and velocity of the rolls. We naturally seek to make the rate of reduction as great as possible, in order to accelerate the rolling and not to employ a greater number of passes than is actually necessary, but in order to work smoothly, and manufacture bars free from seams and fins, the rate of reduction and number of passes must be varied accordingly. [Note. A common rate of reduction in rolling rails and beams is 1·3 : 1. In rolling band iron it is often 2 : 1.] Not only should the iron be entered in each pass without difficulty, and the pressure such that the iron will not squeeze out at the open or loose parts of the groove, but neither should the pressure be so light as not to cause the iron to fill the groove. The rate of reduction may be greater, as the velocity and resistance of the rolls are greater, as the iron is stronger, hotter, more easily worked, and as its geometrical shape experiences less changes in the passage from one groove to the next. It is impossible, therefore, to determine the most favorable rate of reduction according to any one precise and invariable rule.



Let ABF, abf, represent a pair of 16 inch rolls, with the metal, MM, between them, and $A'B'F'$, $a'b'f'$, a pair of 8 inch rolls, and let θ denote the angle AOB, which subtends the arc of contact AB.

The amount of reduction being the same, it is obvious that rolls of small diameter have a greater tendency to elongate the metal than those of larger diameter, the latter spreading it more, so that a bar which exactly fills a groove in a pair of 8 inch rolls, will over-fill a groove of the same size in a pair of 16 inch rolls.

The relation between the velocities of the metal on either side of the rolls, and the velocity of the rolls, has never been investigated that we are aware of. We know that the metal issues with a velocity greater than that of the circumference of the rolls, and we are inclined to believe that the velocity of the circumference of the rolls is a mean between the velocities of the metal on each side. The fact that the metal is never found "banked up" at the points A and A' has led some to infer that the metal must enter with the velocity of the circumference of the rolls, but we hardly think the inference is correct, because we do not believe that the friction between the metal and the rolls is ever sufficiently great to overcome the cohesion of the molecules of the metal, so that instead of the metal being squeezed out at the centre more than at the surface, we believe that it is squeezed out equally and bodily in both directions, and yet carried forward through the groove at the same time. Although the question may perhaps be of no practical importance, it is a curious one and we would like to see it satisfactorily explained. Whatever the truth is, it is evident that there must be a slight slip somewhere between the metal and the rolls, but precisely where that slip takes place we are unable to say.

The Gearing.—The amount of gearing employed in driving roll trains has of late years been reduced to a minimum by the introduction of independent and direct acting engines. Formerly, when the slow moving, low pressure, condensing engine was the standard engine for driving rolling mills, a large amount of gearing was necessary in order to obtain the requisite speed in the rolls; but the quick moving, high pressure, cut off engine, has superseded almost entirely the old condensing engine, so that we are now enabled to drive roll trains directly at the speed required.

Let n be the number of teeth on each pinion, and f' the coefficient of friction. The counter efficiency of each gear in the pinions then will be given by the formula (Rankine's Millwork and Machinery, page 439),

$$c = 1 + 2\pi\frac{f'}{n}. \qquad (3.)$$

Notation and General Formulæ.—We will now proceed to investigate the principles which determine the efficiency of the three most important mills of the present day; the "three high" mill, the clutch reversing mill, and Mr. Ramsbottom's reversing mill; assuming that there are in each case two sets of rolls, the "roughing" and "finishing," and that the engine is attached directly to the train in the first and last mentioned mills.

The efficiency of the mill will depend upon its construction, and and will vary with the position of the metal in the train, so that it must be calculated for each pass separately. In the formulæ which we are about to give we shall adopt the following notation:

P = Pressure due to the amount of reduction of the metal.
p = Pressure due to the weight of the metal.
W_1 = Weight of bottom roughing roll.
W_2 = Weight of middle roughing roll.
W_3 = Weight of top roughing roll.
W_4 = Weight of bottom finishing roll.
W_5 = Weight of middle finishing roll.
W_6 = Weight of top finishing roll.
W = Total weight of all the rolls.
W' = Weight of a single pinion.
L = Total length of all the rolls.
l = Length of a single pinion.
T = Time of pass.
t = Time occupied in the performance of useful work.
a = Angular velocity of the rolls.
R = Radius of circle whose area is the mean sectional area of the rolls and pinions.

(4.) r = Mean radius of gyration of the train $= \frac{1}{2} R\sqrt{2}$.

f = Coefficient of friction (between cast iron and brass).

g = Force of gravity = 32·1695 feet.

(5.) w_0 = Useful work performed $= (2P + p) \frac{a^2}{2g}$.

w_1, w_2, w_3, w_4, w_5, and w_6 = The work performed by each roll respectively. Corresponding to W_1, W_2, etc.

c_1, c_2, and c_3 = The counter efficiency of the bottom, middle, and top rolls respectively.

E = Efficiency of mill.

The value of R is a difficult thing to obtain accurately, but, since the weight of a cubic foot of cast iron averages 444 lbs., the mean sectional area of the rolls and pinions πR^2, (in square feet), may be obtained approximately by dividing the total weight of the rolls and pinions by 444 and by the total length of the rolls and pinions (in feet), so that for an approximate value of R, we have the formula,

$$(6.)\qquad R=\sqrt{\frac{W+2W'}{444\pi\,(L+2l)}}$$

Combining this with equation 4, we obtain,

$$(7.)\qquad r^2=\frac{W+2W'}{888\pi\,(L+2l)}.$$

"*Three high*" *Mill.*—The efficiency of the "three high" mill depends upon whether the engine is attached to the bottom or middle pinion, and whether the middle roll is adjustable or fixed in the housings. In the ordinary arrangement, the middle roll is adjustable and the great objection to it is that the upward pressures upon it have to be transmitted through the chucks and journals of the top roll before reaching the housings. The fixed middle roll is a much better arrangement, as both the upward and downward pressures upon it are then transmitted directly to the housings. For the general formula of the efficiency of this mill, therefore, we have,

$$(8.)\qquad E=\frac{(2P+p)\frac{a^2}{2g}}{c_1(w_1+w_4)+c_2(w_2+w_5)+c_3(w_3+w_6)+(c_1+c_2+c_3)\;W'T\frac{a^2}{2gt}}$$

and since $\frac{a^2}{2g}$ is a factor common to w_1, w_2, w_3, etc.; if the component factors—for convenience sake—be denoted by x_1, x_2, x_3, the above equation reduces to,

$$(9.)\qquad E=\frac{(2P+p)}{c_1(x_1+x_4)+c_2(x_2+x_5)+c_3(x_3+x_6)+(c_1+c_2+c_3)\;W'\frac{T}{t}}$$

and is modified as follows :

When the engine is attached to the bottom pinion (Eq. 3), $c_1=\frac{1}{f}$

$$c_2=\frac{c}{f}=\frac{1+2\pi\frac{f'}{n}}{f},\quad c_3=\frac{c^2}{f}=\frac{\left(1+2\pi\frac{f'}{n}\right)^2}{f}.$$

When the engine is attached to the middle pinion,

$$c_1=c_3=\frac{c}{f}=\frac{1+2\pi\frac{f'}{n}}{f},\qquad c_2=\frac{1}{f}.$$

CASE 1.—When the metal is in the lower grooves of the roughing rolls, and the middle roll adjustable—that is, not fixed,

$$x_1 = (P + p) + W_1 \frac{T}{t}.$$

$$x_2 = (P - W_2) + (W_2 + W_3)\left(\frac{T}{t} - 1\right).$$

$$x_3 = (P - W_2) + W_3\left(\frac{T}{t} - 1\right).$$

$$x_4 = W_4 \frac{T}{t}, \quad x_5 = (W_5 + W_6)\frac{T}{t}, \quad x_6 = W_6 \frac{T}{t}.$$

CASE 2.—When the metal is in the lower grooves of the roughing rolls and the middle roll fixed, the values of x_1, x_4, and x_6, are the same as in the preceding case, and,

$$x_2 = P + W_2\left(\frac{T}{t} - 2\right), \quad x_3 = W_3 \frac{T}{t}, \quad x_5 = W_5 \frac{T}{t}.$$

CASE 3.—When the metal is in the upper grooves of the roughing rolls and the middle roll adjustable, the values of x_4, x_5 and x_6 are the same as in case 1, and,

$$x_1 = W_1 \frac{T}{t}, \quad x_2 = (P + p) + W_2 \frac{T}{t}, \quad x_3 = P + W_3\left(\frac{T}{t} - 2\right).$$

CASE 4.—When the metal is in the upper grooves of the roughing rolls, and the middle fixed, the values of x_1, x_2 and x_3 are the same as in the preceding case, and x_4, x_5, and x_6, the same as in case 2.

CASE 5. When the metal is in the lower grooves of the finishing rolls, and the middle roll adjustable,

$$x_1 = W_1 \frac{T}{t}. \qquad x_2 = (W_2 + W_3)\frac{T}{t}. \qquad x_3 = W_3 \frac{T}{t}.$$

$$x_4 = (P + p) + W_4 \frac{T}{t}. \quad x_5 = P + W_5\left(\frac{T}{t} - 2\right) + W_6\left(\frac{T}{t} - 1\right).$$

$$x_6 = (P - W_5) + W_6\left(\frac{T}{t} - 1\right).$$

CASE 6. When the metal is in the lower grooves of the finishing rolls, and the middle roll fixed, the values of x_1, x_3, and x_4 are the same as in the preceding case, and

$$x_2 = W_2 \frac{T}{t}. \quad x_5 = P + W_5\left(\frac{T}{t} - 2\right). \quad x_6 = W_6 \frac{T}{t}.$$

CASE 7. When the metal is in the upper grooves of the finishing rolls, and the middle roll adjustable, the values of x_1, x_2 and x_3 are the same as in case 5, and

$$x_4 = W_4 \frac{T}{t}. \quad x_5 = (P + p) + W_5 \frac{T}{t}. \quad x_6 = P + W_6 \left(\frac{T}{t} - 2\right).$$

CASE 8. When the metal is in the upper grooves of the finishing rolls, and the middle roll fixed, the values of x_1, x_2, and x_3, are the same as in case 6, and x_4, x_5, and x_6, the same as in the preceding case.

The Clutch Reversing Mill.—In the common clutch reversing mill, five spur wheels are required beside the pinions; two of these are on the same axle and run in opposite directions. To each of these wheels is attached a clawed clutch, the claws of which are placed in opposite directions; and into these claws is moved alternately a clutch, which slides upon feathers fixed to or forged on the main shaft (*Jour. Iron and Steel Institute*, May 1, 1871). Two of the wheels (not on the same axle) are larger than the other three, the arrangement being such that in one direction of rolling, these two always drive the train, while the smaller ones run idle. In the other direction of rolling, the reverse of this is the case. The efficiency at any pass, therefore, will depend upon the direction of the rolling.

Let s_1 and s_2 = The weight each of the two larger wheels.

s_3, s_4 and s_5 = The weight each of the three smaller wheels.

S_1 = The total weight of the two larger wheels.

S_2 = The total weight of the three smaller wheels.

n_1, n_2, &c. = The number of teeth on each wheel respectively, corresponding to s_1, s_2, &c.

a_1, a_2, &c. = The angular velocities of each wheel respectively, corresponding to s_1, s_2, &c.

c' = The counter efficiency of the two larger wheels.

c'' = The counter efficiency of the three smaller wheels.

w' = The work performed against the resistance of the wheels.

Then,

$$(10.) \qquad w' = \left\{ \frac{c'}{f} \left(s_1 a_1^2 + s_2 a_2^2\right) + \frac{c''}{f} \left(s_3 a_3^2 + s_4 a_4^2 + s_5 a_5^2\right) \right\} \frac{t}{2g};$$

in which,

$$(11.) \qquad c' = 1 + \pi f' \left(\frac{1}{n_1} + \frac{1}{n_2}\right),$$

and,

(12.) $$c'' = 1 + \pi f' \left(\frac{1}{n_3} + \frac{1}{n_4} + \frac{1}{n_5}\right).$$

If the two larger wheels are of the same pattern and also the three smaller ones, we have $s_1 = s_2$, $s_3 = s_4 = s_5$, $n_1 = n_2$, $n_3 = n_4 = n_5$, $a_1 = a_2 = a_3 = a_4 = a_5 = a$, and,

(13.) $$w' = \left(\frac{c'}{f} S_1 + \frac{c''}{f} S_2\right) \frac{a^2}{2g},$$

in which,

(14.) $$c' = 1 + 2\pi \frac{f'}{n_1},$$

and,

(15.) $$c'' = 1 + 3\pi \frac{f'}{n_3}.$$

And even if the wheels are all of different patterns, and n_1 and n_3 denote the mean number of teeth on the wheels to which they correspond, equation 13 will be sufficiently accurate for all practical purposes.

Since the moment of inertia of the rolls is (approximately) $\frac{(W + 2W')^2}{888\pi(L + 2l)}$, (Eq. 7), the work performed at each reverse will be $(c_1 + c_3) \frac{(W + 2W')^2}{444\pi(L + 2l)} \frac{a^2}{2g}$. For the efficiency of the mill, therefore, we obtain the general formula, (16.)

$$E = \frac{2P + p}{c_1(x_1 + x_4) + c_3(x_3 + x_6) + (c_1 + c_3) W' + \frac{1}{f}(c' S_1 + c'' S_2) + (c_1 + c_3) \frac{(W + 2W')}{444\pi(L + 2l)}}$$

which is modified as follows:

When the two larger wheels are the drivers,

$$c_1 = \frac{c'}{f} = \frac{1 + 2\pi \frac{f'}{n_1}}{f}$$

$$c_3 = \frac{cc'}{f} = \frac{\left(1 + 2\pi \frac{f'}{n}\right)\left(1 + 2\pi \frac{f'}{n_1}\right)}{f}.$$

When the three smaller wheels are the drivers,

$$c_1 = \frac{c''}{f} = \frac{1 + 2\pi \frac{f'}{n_3}}{f}.$$

$$c_3 = \frac{cc''}{f} = \frac{\left(1+2\pi\frac{f'}{n}\right)\left(1+3\pi\frac{f'}{n_3}\right)}{f}.$$

CASE 1. When the metal is in the roughing rolls,

$$x_1 = P+p+W. \quad x_3 = P-W_3. \quad x_4 = W_4. \quad x_6 = W_6.$$

CASE 2. When the metal is in the finishing rolls,

$$x_1 = W_1. \quad x_3 = W_3. \quad x_4 = P+p+W_4. \quad x_6 = P-W_6.$$

Ramsbottom's Reversing Mill.—In this mill the fly-wheel is dispensed with altogether, and the boiler is made the sole reservoir of power, so that by reversing the engines, the rolls are reversed at will. The five spur wheels required in the common clutch reversing mill are also dispensed with, and the counter efficiency of the gearing, therefore, is constant. In every instance, we have,

$$c_1 = \frac{1}{f}, \text{ and } c_3 = \frac{c}{f};$$

which gives us for the general formula,

$$\text{(17.)} \quad E = \frac{(2P+p)f}{x_1+x_4+c(x_3+x_6)+(1+c)W'+(1+c)\frac{(W+2W')_2}{444\pi(L+2l)}f}.$$

The values of x_1, x_3, x_4, and x_6 are modified as in the common clutch reversing mill. All the other quantities are constant.

Conclusion.—The above formulæ have been calculated on the assumption that in each instance there are but two sets of rolls, the "roughing" and "finishing;" but it is obvious that they may be easily extended, so as to include three and even more sets. In reducing the above formulæ to figures, the great difficulty is to obtain reliable data. By assuming the requisite data, however, and making it uniform in each case, we may obtain figures which will probably be a fair comparison of their efficiencies. But it seems to us that it would be advisable for some of our iron and steel associations to give each of these and other systems, a fair trial, and so decide the question in a way that admits of no discussion. We have had trials of almost every kind of boiler and steam engine, but none at all of any kind of rolling mill that we are aware of, and we are disposed to believe that the questions connected with the construction of the class of machinery under consideration, have not received sufficient attention at the hands of really competent engineers.

There is no such thing in existence as a thoroughly good treatise on rolling mill machinery. On the chemical changes wrought in smelting and puddling furnaces, on the character of ores, and the mechanical properties possessed by the finished product, have apparently been concentrated all the energies of those who have made iron and steel their special study; while the details of roll trains have been passed over with very little notice. All that can be learned about the subject from books is embodied in a few desultory chapters and certain sets of engravings, which, however, admirable as drawings, only represent, after all, indifferent practice. The mathematical principles which determine the best forms and proportions to be imparted to the different parts of the mechanism, have been almost entirely ignored. The best literature on the subject is to be found in the engineering periodicals of the day.

Some valuable experiments, however, were recently made by Mr. Rupert Boeck, with the idea of determining the actual amount of power consumed in rolling sheet iron. "The moment of inertia of the fly-wheel, by careful calculation, was found to be 184,516 foot pounds, its weight being 65,300 pounds. The friction of the fly-wheel on its journal alone consumed 16·8 horse power, which, added to the effort required to overcome the friction of the other parts of the mill, gave for the total effort exerted in running the mill empty, 56·5 horse power. The experiments were made on a plate of boiler iron, which had the following dimensions when trimmed: length, 15 feet; width, 41 inches; and thickness, $\frac{1}{2}$ inch. The rolls were nearly 28 inches in diameter."—(See the *Iron Age*, July 23, 1874, page 24.) From the results of these experiments, it seems to be about a fair estimate to assume $P = 50{,}000$ lbs. For the coefficients of friction we have (Haswell) f (cast iron upon brass, tallow unguent) $=$ ·103, and f' (cast iron upon cast iron, soap unguent) $=$ ·197. For the remaining data, let us assume the following convenient and not unreasonable values:

$p = 10{,}000$ lbs, $W_1 = W_2 = W_3$, etc. $= 10{,}000$ lbs, $W' = 1000$ lbs., Length of each roll $=$ 6 ft., $l = 1$ ft., $T = 20$ sec., $t = 10$ sec., $n = 20$, $n_1 = 50$, $n_3 = 35$, $S_1 = 4000$ lbs., $S_2 = 5000$ lbs. The efficiency respectively corresponding to each of the preceding cases then will be as follows:

In the "Three-high" mill.	Cases 1 & 5 E =	Cases 2 & 6 E =	Cases 3 & 7 E =	Cases 4 & 8 E =
Eng. attached to bottom pin.,	·038867	·050172	·044828	·04894
" " " middle "	·040096	·051332	·04647	·050904

The average for adjustable middle roll (cases 1, 3, 5 and 7), engine attached to bottom pinion, is 0·041848.

The average for adjustable middle roll, engine attached to middle pinion, is 0 043283.

The average for fixed middle roll (cases 2, 4, 6 and 8), engine attached to bottom pinion, is ·049556.

The average for fixed middle roll, engine attached to middle pinion, is ·051118.

In the Clutch Reversing Mill.	Cases 1 & 2. E =
When the two larger wheels drive, . . .	·045190
" " three smaller " " . . .	·044033

In *Mr. Ramsbottom's Reversing Mill*, cases 1 and 2, E = ·048118.

The ratio, then, of the greatest efficiencies of the three mills respectively in the order of their consideration, is as, ·051118 : ·04519 : ·048118.

Cornish Pumping Engines.—The following is extracted from the *Mining Journal* of April 1, 1876. The number of pumping engines reported for February is 17. They have consumed 1657 tons of coal, and lifted 12,900,000 tons of water 10 fms. high. The average duty of the whole is, therefore, 52,700,000 lbs., lifted 1 ft. high, by the consumption of 112 lbs. of coal. The following engines have exceeded the average duty :—

Crenver and Wheal Abraham—Sturt's 90 in., Millions	63·1
" " " " —Pelly's 80 in., .	52·7
" " " " —Willyam's 70 in., .	79·9
Dolcoath—85 in.	52·7
West Basset—Grenville's 70 in.	53·8
" " —Thomas' 60 in.	58·8
West Tolgus—Richard's 70 in.	53·0
West Wheal Seton—Harvey's 85 in. . . .	62·6