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Formation of ribs on rotating rollers

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When thin films of liquid are produced by rolling it is commonly observed that the liquid film is not uniform but has regularly spaced thick lines or ribs. This phenomenon has been studied experimentally and it was found that the onset of ribbing was governed by the relation $\eta S/\gamma = 10{\cdot}3\ (g/R)^{\frac{3}{4}}$. At higher values of the parameter $\eta/S\gamma$ the number of ribs per centimetre increased sharply. At values of $\eta S/\gamma > 2{\cdot}4$ the rib number became independent of this parameter and varied solely with the geometrical parameters of the system, i.e. roller radius and gap.

Introduction

Many industrial processes require thin films of viscous liquid to be spread uniformly on a solid surface. Different methods of application are employed, e.g. brushing, spreading or rolling, but in all cases the resultant film is often non-uniform in thickness or 'ribbed'. This ribbed pattern often appears regular (Chalmers & Hoare 1937, 1941), thereby suggesting that the phenomenon is well defined in terms of the properties of the liquid and the conditions of application.

The formation of the rib pattern does not seem to have been studied intensively. Smith, Orchard & Rhind-Tutt (1961) reported the similarity between brush-marking and the pattern formed by a V-shaped spreader. They claimed that a film free of ribbing is formed by a trailing blade with a knife edge. Sone, Fukushima & Fukada (1960) published a short account of the changes in rib pattern with speed when milling butter. Pitts & Greiller (1961) and Pearson (1960) have made attempts to treat the problem theoretically, starting with the basic equations of lubrication theory and then considering disturbances of the shape of the liquid meniscus on the outgoing side of the nip which might result from changes in pressure occurring inside the liquid. These authors derive the same sort of dimensionless parameters on which the rib formation might be expected to depend, but the calculation of the actual spacing seems to lack precision, possibly because of uncertainty as to what boundary conditions have to be satisfied.

In the work reported here experiments have been made to determine the critical conditions for rib formation on rotating rollers, and the manner in which the pattern varied with changes in speed, roller separation, viscosity, surface tension and roller dimensions.

Apparatus

The apparatus consists of a pair of rollers mounted one above the other. The lower roller is of brass, $2{\cdot}875$ cm in radius and $9{\cdot}75$ cm long. It is mounted in ball races set in the side frames of the apparatus and was unchanged throughout the experiments. The upper roller is mounted in phosphor bronze journal bearings set in blocks which slide in the side frames. This roller was one of three duralumin rollers of radii 2·175, 2·875 and 3·85 cm respectively. The peripheral speeds of the two rollers were made equal by a suitable arrangement of gears. The rollers were driven by a constant speed motor through a variable speed hydraulic gear and a gear train. A tachometer is used to measure the roller speed in rev/min. All the rollers were turned between centres to an accuracy of $\pm$ 0·00025 in. for parallelism and $\pm$ 0·0002 in. for concentricity. The rib formations observed in practice were regularly spaced and stable, thus indicating that these tolerances were satisfactory for this work. The bearing blocks of the upper roller rested on strong springs so that the rollers were held apart. Micrometers mounted on the side frames and thrusting against the top surfaces of the bearing blocks were used to adjust the gap between the rollers to any desired value. The liquid under test was contained in a trough mounted beneath the lower roller in a position where the roller dipped into the liquid. With this arrangement the roller always carried from the trough sufficient liquid to flood the nip. Excess liquid was prevented from being forced sideways toward the bearings by side plates in contact with the roller ends.

Procedure

Setting the rollers

The gaps between the rollers were selected to be 0·001, 0·003, 0·005, and 0·007 in. Before each experiment these gaps were set using feeler gauges, the roller position being adjusted by means of the micrometers. The adjustment was made for at least three positions around the circumferences of the rollers and the micrometer readings for each setting averaged. This procedure facilitated the alteration of the roller separation in the course of the experiment.

Counting the ribs

It was not found easy to count the ribs at the highest speeds employed, so flashlight photographs were taken and the ribs counted on the negative. To increase the contrast between the ribs and the roller background a small quantity of dye was dissolved in the oil and a high-contrast developer used. After development the film was placed in a photographic enlarger and the image focused on a sheet of white paper. The trough containing the liquid carried scribed lines 3 cm apart and the frequency on the roller was obtained by counting the number of ribs between these marks. In most cases the technique proved completely satisfactory but some difficulty was experienced with the 0·001 in. gap because of the low contrast between ribs and background.

Critical conditions

In the main body of the experiments three speeds of rotation, viz. 50, 100, 200 rev/min, were employed, as these were thought to cover the range of commercial speeds of application of varnishes and adhesives. With liquids of low viscosity, it was found possible to observe the speed at which ribbing commenced, so a series of experiments was made to determine the critical conditions for a number of liquids.

The procedure adopted was to set the gap between the rollers as described above and to increase the speed of rotation from zero until ribs were observed on the rollers. Several determinations were made and the mean value of the speed taken to be the critical one. The rollers were then reset to a new gap and the observations repeated. Some scatter in the results occurred because it was not easy to spot the initial rib formation and, at the low speeds of rotation necessary, the angular velocity of the rollers was not quite constant.

Materials

In all, nine liquids were used in the main experiments with viscosities ranging from 0·21 to 22·9 P. The liquids were paraffin or vegetable oils; aqueous solutions were avoided to eliminate the possibility of changing concentration due to variations in ambient relative humidity. In addition, a few other low-viscosity liquids were used in the experiments to determine the critical conditions. The viscosity of each liquid was measured in a Ferranti–Shirley viscometer. The surface tensions of the more viscous liquids were measured using the capillary rise method; for other liquids the De Nouy tensometer was used. Viscosities were measured at 25 °C; surface tension measurements and the ribbing experiments were performed in a room controlled at 25 ± 1 °C.

Results

(a) *Factors affecting rib spacing*

In this series of experiments all nine liquids were used. Three speeds of rotation, three pairs of rollers and four gap settings were investigated. The number of ribs/cm (n) for each oil at each value of the other variables was read off the photographs and tabulated. As mentioned earlier, some values at the smallest gap setting were missing because of difficulty in deciphering the photographs although ribs could be seen by eye. From the theoretical treatment of the phenomenon mentioned earlier (Pitts & Greiller 1961; Pearson 1960) it was to be expected that the rib spacing would depend on the parameter $\eta S/\gamma$, where η = viscosity, S = peripheral speed of rollers and γ = surface tension. Plotting rib number, n, against $\eta S/\gamma$ showed that n increased rapidly and that above a viscosity level of about 2·4 P it was independent of viscosity and speed (the surface tension was neglected here because its variation was small for the oils used). The hypothesis that rib number was independent of liquid and speed at these levels was tested statistically by analysis of variance and shown to be correct. Consequently, the rib numbers for these liquids and speeds were averaged for each roller-pair/gap combination. The means, which can be regarded as the upper

Gap	Combination A	Combination B	Combination C
1	12·4	11·3	10·4
3	9·1	8·3	7·9
5	6·7	6·5	6·0
7	5·0	4·9	4·7

TABLE 1. Experimental values of N. For details of combinations, see table 2.

limit, N, of the rib number likely to be observed for the particular geometry over the speed range used, are given in table 1. The standard deviation for each setting was also calculated. In most cases it was about 0·5 (15 estimates) but tended to be higher for the smallest gap, where fewer estimates were available.

From the theoretical study of this problem, which is based on lubrication theory, the appropriate length parameter, depending solely on the rollers, to use

Gap 10^{-3} in.	Linseed oil. $\eta = 0{\cdot}46$, $\gamma = 35{\cdot}6$			Paraffin I. $\eta = 1{\cdot}21$, $\gamma = 31{\cdot}6$			Paraffin II. $\eta = 0{\cdot}42$, $\gamma = 31{\cdot}0$			Paraffin III. $\eta = 0{\cdot}21$, $\gamma = 31{\cdot}0$		
	50 rev/min	100 rev/min	200 rev/min	50 rev/min	100 rev/min	200 rev/min	50 rev/min	100 rev/min	200 rev/min	50 rev/min	100 rev/min	200 rev/min
Roller combination A. Roller radii 2·175 and 2·875 cm												
1	—	—	12·8	—	—	—	10·0	10·8	11·8	—	—	—
3	4·0	6·5	7·3	6·6	7·7	9·0	4·5	6·4	7·0	0	4·9	6·8
5	1·9	3·9	5·1	5·0	5·4	5·8	1·9	4·1	4·8	0	1·7	3·6
7	0	2·4	3·4	3·5	4·2	4·3	0	2·4	3·5	0	0	2·2
Roller combination B. Roller radii 2·875 and 2·875 cm												
1	8·7	9·2	9·3	—	—	—	—	—	—	10·0	—	—
3	4·0	5·8	6·4	6·6	7·7	9·0	6·3	7·3	8·2	2·2	4·7	6·6
5	1·9	3·7	4·2	5·0	5·4	5·8	3·0	4·7	5·2	0	2·0	3·5
7	0	2·5	3·3	3·5	4·2	4·3	0	3·0	4·0	0	0	2·4
Roller combination C. Roller radii 3·850 and 2·875 cm												
1	9·0	10·1	11·7	—	—	—	—	—	—	9·1	10·6	11·4
3	4·9	5·2	8·0	7·8	7·2	7·7	5·6	7·3	7·8	3·0	5·1	6·6
5	2·3	3·7	4·8	4·5	5·3	5·5	3·0	4·0	4·7	0	2·8	3·9
7	1·4	2·9	3·5	3·5	4·1	4·0	1·7	3·1	3·8	0	1·5	2·7

Notes. To convert rev/min to cm/sec multiply by 0·3. η and γ in P and dyne/cm respectively. — = confused picture; unable to count ribs. 0 = no ribs formed at this setting.

TABLE 2.

in the work is the total curvature given by $1/r = 1/R_1 + 1/R_2$, where R_1, R_2 are the radii of the individual rollers. Table 1 thus gives the values of N for various values of r and g (gap width). Consideration of the table shows that, within the limits of experimental error, (a) the ratios of the columns r_a:r_b:r_c are independent of g, and (b) the ratios of the rows g_1:g_2:g_3:g_4 are independent of r, and we deduce that the relation between N, r and g is of the form $N(r, g) = N\phi(r)\,\theta(g)$. The remaining experimental data are given in table 2. In this table the values of n for different liquids at various r, g levels are listed. It can be seen that n falls to zero at a definite value of $\eta S/\gamma$ which depends on (r, g). If n is plotted against $\eta S/\gamma - (\eta S/\gamma)_0$, curves of the type shown in figure 1 are obtained. Furthermore, if n/N is plotted against this parameter the points seem to be scattered around a single curve which suggests that the relative rib number is independent of r and g. It appears from this analysis, therefore, that the rib number is determined by independent functions of the three parameters, r, g and $\eta S/\gamma$.

(*b*) *Critical conditions*

In order to study the critical conditions for the onset of ribbing, it was necessary to use only liquids with viscosities less than 2 P. Some liquids of low viscosity not employed in the earlier experiments were therefore used in this study. The

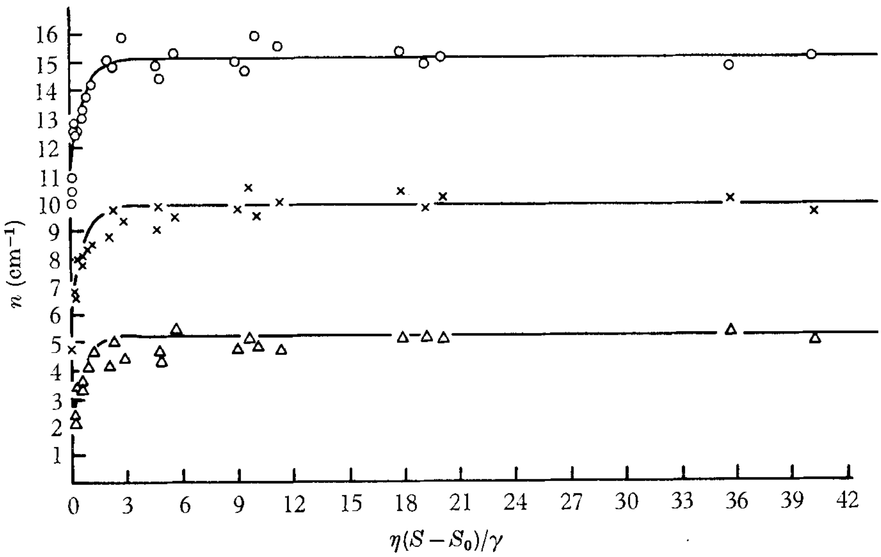

FIGURE 1. Roller combination A. n against $\eta(S-S_0)/\gamma$. $\triangle$, g = 0·007 in.; ×, g = 0·005 in., points lifted by 3 units; ○, g = 0·003 in., points lifted by 6 units.

Gap	Dibutyl phthalate. η = 0·17, γ = 35·0	Glycerol mono-oleate. η = 0·37, γ = 30·0	Olive oil. η = 0·73, γ = 33·0	Linseed oil. η = 0·46, γ = 35·6	Paraffin I. η = 1·21, γ = 31·6	Paraffin II. η = 0·42, γ = 31·0	Paraffin III. η = 0·21, γ = 31·0
			Roller combination A				
1	40	18	12	25	3	15	—
3	92	42	26	41	12	35	72
5	137	63	37	56	17	50	95
7	208	83	46	72	22	67	130
			Roller combination B				
1	35	15	9	19	—	—	—
3	75	39	20	33	10	27	55
5	110	53	31	47	25	40	85
7	150	70	39	60	30	55	115
			Roller combination C				
1	30	12	8	—	—	7	—
3	67	32	17	25	5	25	47
5	98	46	25	36	15	33	75
7	138	62	31	46	17	42	82

TABLE 3. Critical rev/min for the onset of ribbing. Units as for table 2.

method of estimating the critical conditions was to preset the gap between the rollers and increase the speed until ribs were observed. At least three estimates of speed were made for each set of conditions and the results averaged. The complete set of data obtained in these experiments is contained in table 3.

Pitts & Greiller (1961) deduce that the critical conditions for the onset of ribbing are given by the relation

$$\eta SR/\gamma g = \text{const.},$$

so that plotting $\eta S/\gamma$ against g/R should give a straight line. Using the data of table 3 there was a fair amount of scatter, but the graph appeared to be curved. The scatter could be due to the difficulty in observing precisely the formation of ribs and possible small variations in gap setting. However, because the graph appeared curved the data were studied systematically. Table 3 shows the variation in critical speed with the parameter γ/η for twelve combinations of r, g. A plot of S against γ/η for any roller-pair/gap combination gives a straight line with small scatter. The slopes of the twelve lines were calculated using the method of least squares and it can readily be shown that, for any given roller pair, the slope of the line is proportional to $g^{\frac{3}{4}}$. The dependence on roller radius was not so easily obtained.

In the work four rollers were used, of which two had equal diameters. If for convenience we designate the rollers as A, B_1, B_2 and C with radii R_a, R_b, R_c the roller pairs used were (A, B_2), (B_1, B_2), (C, B_2). If, as in the previous section, the combined curvature, e.g. $1/r_a = 1/R_a + 1/R_b$, was used in the ratio g/r, the resultant plot of log (slope) against log g/r was curved. On the other hand the plot of log (slope) against log (g/R) gave a straight line of slope $\frac{3}{4}$. A plot of the slopes (i.e. $\eta S/\gamma$) against $(g/R)^{\frac{3}{4}}$ is shown in figure 2. The slope of the best line through the points was calculated to be 10·3, and the critical conditions for the onset of ribbing satisfy the relation

$$\frac{\eta S}{\gamma}\left(\frac{R}{g}\right)^{\frac{3}{4}} = 10{\cdot}3.$$

Discussion

As was to be expected, following the theoretical work of Pitts and Pearson, the parameter $\eta S/\gamma$ is one of the factors governing the onset of ribbing. The other factor $(g/R)^{\frac{3}{4}}$ was not expected on two grounds: (1) that theory predicts (g/R) as the appropriate factor, and (2) that the radius involved is that of the interchangeable roller itself and not the equivalent radius obtained from the combined curvature. In the experiments reported by Pitts this distinction did not arise, because he used pairs of equal rollers. The value of $(\eta S/\gamma)(R/g)^{\frac{3}{4}}$ obtained in this work is of the same order as predicted by Pitts.

However, the present work confirms that, in all industrial processes where thin films are involved, the application of the film by rollers without ribbing is impossible except at uneconomically low speeds. Films free of ribbing can however be obtained if the direction of rotation of one of the rollers is reversed. It has been shown that, once ribbing has begun, the frequency of the ribs increases rapidly with $\eta S/\gamma$. If the data of Pearson's figure 10 are replotted as the number of ribs/cm against $\eta S/\gamma$, as in figure 1, a curve of similar shape is obtained. Furthermore the curve appears to approach a value of N of about 8 for a gap be-

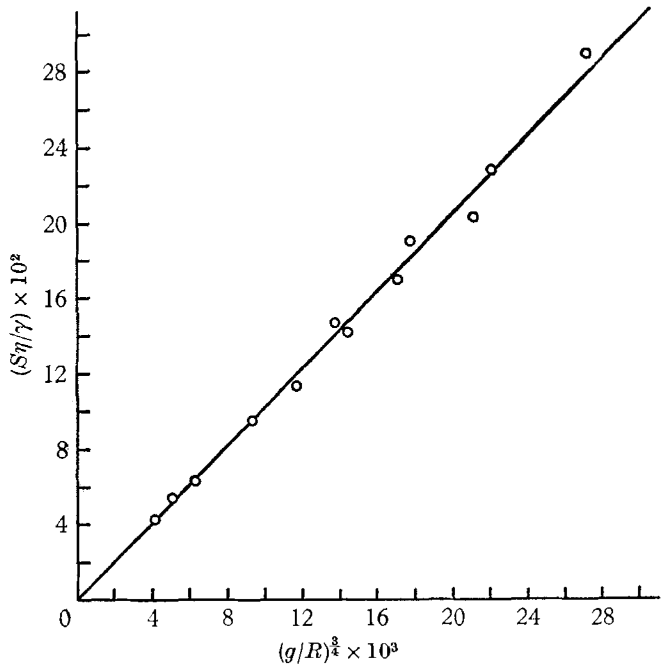

FIGURE 2. Relationship between $S\eta/\gamma$ and g/R for critical conditions.

tween spreader and substrate of 0·004 in. This value of N is intermediate between the values obtained in this work for gaps of 0·003 and 0·005 in. and underlines Pearson's statement that rib formation in rolling and spreading are closely allied.

The frequency of the ribs attains a limiting value which is independent of the liquid and speed of rotation over the range of variables examined. It is determined only by the geometry of the system, but in this case roller radius and gap appear to be acting independently and not as the ratio g/R as is the case for the critical conditions.

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