For a ring-shaped plate the unknown constants are determined from limiting conditions at the outside and inside contours. In that case when the plate has no opening in the center $C_2 = C_4 = C_6$ must be made equal to zero; the remaining constants are computed from limiting conditions at the edge ($r = r_0$).

In Table 1 and Figure 1 are given the cambers w/H in the center of jointly resting and rigidly hooked three-layered plates of various relative thicknesses H/R at different values for the ratio of the shear moduli of the supporting layers and the fillers G_s/G_f which are under the action of a uniformly distributed transverse load (H is the total thickness; R, the plate radius). The data obtained show that the relative increase in the cambers with a decrease in transverse rigidity of the filler is greater for thin plates ($H/R \leqslant 1/20$) than for plates of average thickness.

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EFFECT OF LOADING PARAMETERS ON THE PROCESS OF METAL FRACTURE DURING BLANK PRODUCTION BY BREAKING

V. I. Kosyak UDC 539.3

A study of metal fracture kinetics under different loading conditions is of considerable importance, both from the point of view of developing process theory and in relation to applications. In particular, development of methods for controlling the formation of fracture surfaces is of special importance in designing individual types of technological equipment.

The present work discusses results of studying metal fracture during preparation of blanks by breaking bearing in mind loading conditions. Recommendations are made on the basis of data obtained for improving blank quality.

The most promising method of loading metal for breaking rolled steel for use in existing forging equipment is loading by a bending moment, an axial force, or compression with a liquid, and this requires special equipment [1-5]. However, the quality of measured blanks obtained by bending rolled steel does not always satisfy the requirements given (Fig. 1).

It is well known that growth kinetics for a crack in a loaded element, its path and advance rate depend not only on material mechanical properties, but to a marked degree on the level of such factors as the nature of macrostress distribution and the supply of elastic strain energy in the loading system [6]. Under three-point bending conditions for beam loading when rolled steel is broken the ratio of bar diameter to the distance between supports is quite large, and the size of the contact area of the support with the bar is commensurate with its diameter, curves for transverse force and its bending moment differ markedly from piecewise-linear curves (Figs. 2a and 3a). The greater the area of external load application is on the breaker side, and the smaller it is on the support side, and also the smaller the distance between support and breaker, then the larger is the bending moment gradient along the bar length, and consequently there is a greater difference between stresses in the notch plane and zones adjacent to it [7, 8]. The same kind of bending stress distribution creates favorable conditions for crack development in the notch plane.

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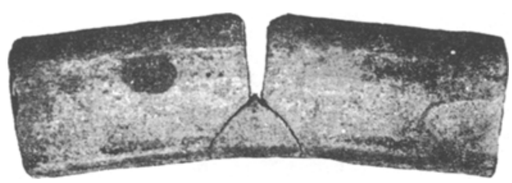


Fig. 1

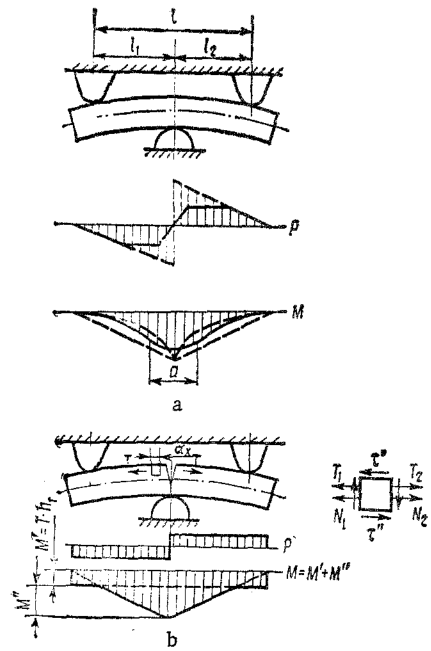


Fig. 2

Fig. 1. A break in steel ShKh15 (ϕ 30 mm) by a single-support scheme with $l = l_{ad} = 90$ mm.

Fig. 2. Diagrams for P and M with bar bending by a single-support scheme ($a \neq 0$) to fracture (a) and during failure (b).

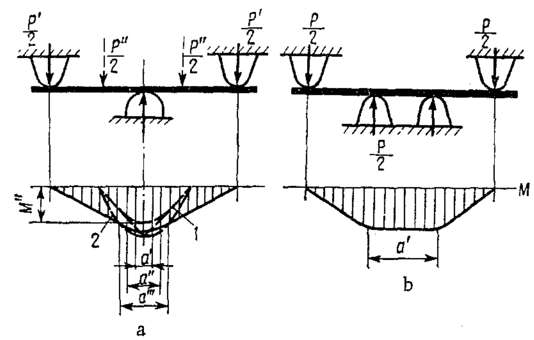


Fig. 3

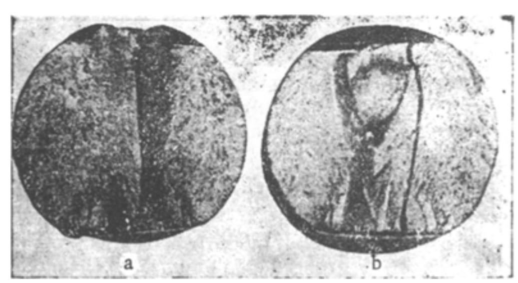


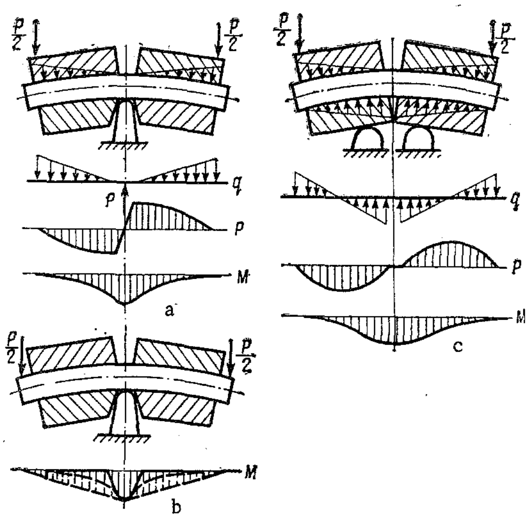
Fig. 4

Fig. 3. Diagrams for M with bar bending by a single-support scheme (a) and a double-support scheme ($a \neq 0$; $l_{ad} = l + a$) (b).

Fig. 4. Breakage of steels ShKh15 (ϕ 30 mm) (a) and 45 (b) by a single-support scheme with $l \approx l_{ad} = 15$ mm.

However, with a reduction in the applied bending load arm and an increase in support diameter there is an increase in the axial extent of the stress distribution zone from support a and with decreasing cylindrical support diameter or flat support width there is an increase in the depth of bar surface crushing. Moreover, there is an increase in the level of tangential stresses due to transverse loading which causes an increase in the chance of growth in the proportion of plastic strain and cleavage failure, thus reducing blank quality (Fig. 4).

With the appearance of crack, the stress distribution in a bent bar changes, since a stretched layer in the adjacent surface tries to contact, causing the occurrence of an additional load T increasing with crack growth during its passage through the stretched zone, and this load is applied from the ruptured layers and directed from the notch plane. On reaching an additional load sufficient for fracture, the level of the initial load automatically drops and further crack advance is governed by conditions for energy exchange between failed and deformed zones; zones adjacent to the crack surface are loaded by tangential stresses whose value depends on loading conditions and material physicomechanical properties caused by the amount and rate of energy transfer.



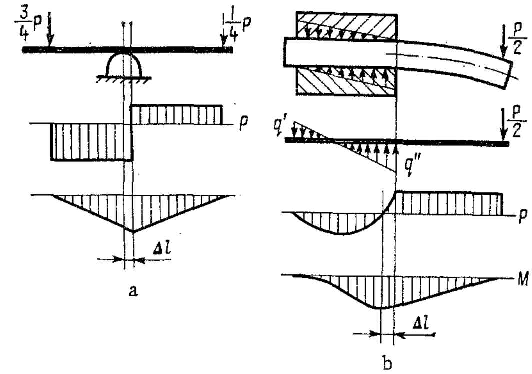


Fig. 5 Fig. 6

Fig. 5. Diagrams for P and M during bar bending in sleeves with bar contact on a support $l_{ad} = 0.8l$ (a), on a support and breakers $l_{ad} = 0.82l$ (b), and with no contact of the bar with support and breakers $l_{ad} = 0.86l$ (c).

Fig. 6. Diagrams for P and M with asymmetric loading caused by unequal bending arms (a) and one-sided limitation of bar deformation (b).

Thus, alongside tangential stresses due to transverse forces

$$\tau' = \frac{PS_{z(y)}}{bI_z} \tag{1}$$

there are tangential stresses due to an additional load from ruptured layers

$$\tau'' = \frac{\Delta T - \Delta N_j}{bdx}, \tag{2}$$

where ΔT is force due to contraction of ruptured layers; ΔN_j is inertial load.

In the case of tangential stresses τ'' reaching a critical value, it is possible for failure of a bent bar to occur by cleavage in the direction of greatest shear stresses, and this causes crack deviation from the notch plane (see Fig. 1).

Use is made of an energy balance for a failed bar in order to evaluate τ''. During bending by a transverse load a bar accumulates potential energy

$$U_b = \frac{P^2a^2b^2}{6EIl} + \frac{3}{5} \cdot \frac{P^2ab}{GFl}. \tag{3}$$

As a result of ruptured layer contraction an elementary volume of deformed material adjacent to the layers absorbs energy by shearing

$$dU_s = \frac{(\tau'')^2}{2G} Fdx, \tag{4}$$

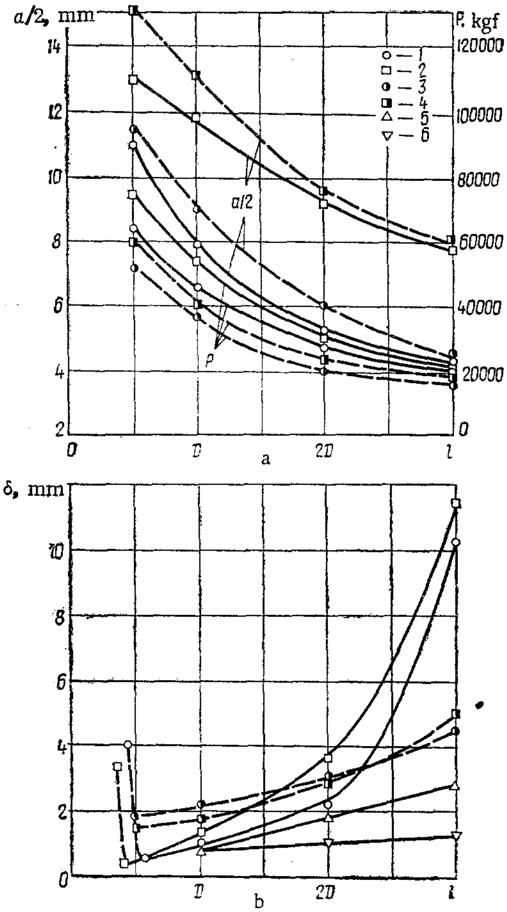
where F is area of the section being considered; E is tensile elasticity modulus; G is shear modulus; I is moment of inertia for the deformed bar.

By assuming a linear shear stress distribution along the bar

$$\tau'' = \tau''_{max}\frac{x}{l}, \tag{5}$$

we obtain an overall value of energy absorbed due to shearing:

$$U_s = \int_0^l \frac{F(\tau''_{max})^2}{2Gl} x^2 dx = \frac{(\tau''_{max})^2}{6G} Fl = \frac{(\tau''_{max})^2}{6G}(D - h_t)Bl, \tag{6}$$



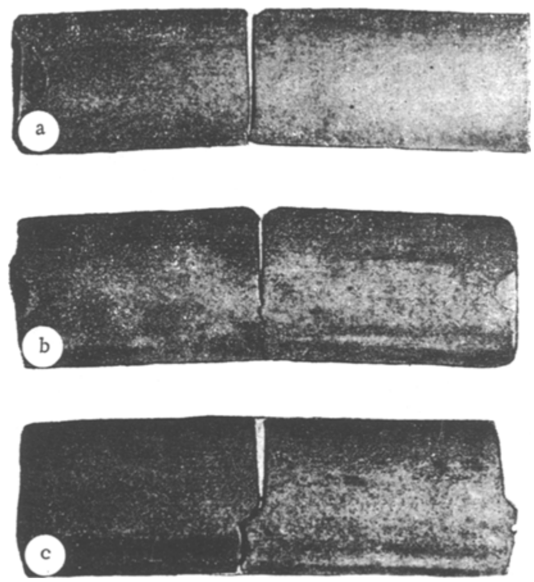


Fig. 7 Fig. 8

Fig. 7. Dependence of fracture force and length of crushed area on bending arm during breakage by a single-support scheme (a), and also the greatest crack deviation from the notch plane (b): 1, 2) steel ShKh15, D_{su} = 40 and 100 mm respectively; 3, 4) steel 45, D_{su} = 40 and 100 mm respectively; 5, 6) steel ShKh15 P_3 = 6000 and 12,000 kgf respectively.

Fig. 8. Breaks in steel ShKh15 bars (ϕ 30 mm) in contact with sleeves on a support with P_3 = 6000 kgf ($l_{ad} = 0.86l$) and with an arm $l_1' = l_2'$ = 30 mm (a); $l_1'' = l_2''$ = 60 mm (b); and $l_1''' = l_2'''$ = 90 mm (c).

where D is the fractured bar diameter; h_t is the crack length; B is the bar width at the crack tip.

Since bending stress gradient with different loading schemes may differ from the distribution with three-point bending (see Figs. 2a, 3, 5, and 6b), instead of l in expression (3) we should put in the adduced applied bending load arm

$$l_{ad} = \frac{\Omega}{M_{max}}, \tag{7}$$

where Ω is the area of the diagrams due to bending moment.

Considering that the second term of Eq. (3) expressing the proportion of energy due to shear by transverse load P does not participate in energy exchange at the precritical stage of fracture, and also that crack development only expends energy for the extended zone of the bent bar $U_e = \frac{1}{2}U_b$, and assuming that potential energy for the extended zone passes without loss into shear energy, we equate expressions (3) and (6) for symmetrical three-point bending taking account of (7):

$$\frac{P^2 l_{ad}^2}{192EI} = \frac{(\tau''_{max})^2 (D - h_t) Bl}{6G}, \tag{8}$$

whence

$$\tau''_{\max} = Pl_{\text{ad}}\sqrt{\frac{3Gl_{\text{ad}}}{96EI\,(D-h_t)\,Bl}}\,, \tag{9}$$

or

$$\tau''_{\max} = k_1 Pl_{\text{ad}}\sqrt{\frac{1}{IB\,(D-h_t)}\cdot\frac{l_{\text{ad}}}{l}}\,, \tag{10}$$

where $k_1 = \sqrt{\frac{3G}{96E}}$ is a coefficient depending on material properties.

Thus, at each point in the section it is possible to compute principal stresses and their orientation relative to the axisof the failed bar:

$$\sigma_1 = \frac{1}{2I}\left[My + \sqrt{M^2y^2 + \frac{4Ik_1^2P^2l_{\text{ad}}^3}{B\,(D-h_t)\,l}}\right];\quad \sigma_2 = 0; \tag{11}$$

$$\sigma_3 = \frac{1}{2I}\left[My - \sqrt{M^2y^2 + \frac{4Ik_1^2p^2l_{\text{ad}}^3}{B\,(D-h_t)\,l}}\right]; \tag{12}$$

$$\operatorname{tg}\alpha_0 = -\frac{2Ik_1Pl_{\text{ad}}\sqrt{l_{\text{ad}}}}{\sqrt{IB\,(D-h_t)\,l}\left[My + \sqrt{M^2y^2 + \frac{4Ik_1^2P^2l_{\text{ad}}^3}{IB\,(D-h_t)\,l}}\right]}\,, \tag{13}$$

and it is also possible to estimate the nature of failure due to known conditions for brittle and ductile fracture

$$\frac{\tau_{\max}}{\sigma_{\max}} \lesseqgtr \frac{\sigma_s}{R_\sigma} \tag{14}$$

or

$$\frac{Ik_1Pl_{\text{ad}}\sqrt{l_{\text{ad}}}}{My\sqrt{IB\,(D-h_t)\,l}} \lesseqgtr \frac{\sigma_s}{R_\sigma}\,, \tag{15}$$

where σ_s is material shear resistance; R_σ is material separation resistance.

It follows from analysis that a reduction in the adduced applied bending load arm increases the bending stress gradient and loading stiffness, as a result of which favorable conditions are guaranteed for crack growth in the notch plane. In addition, for each method with a reduced arm for load application there will be a change in loading regime and parameters for the support crushed area, having in turn an effect on bending moment distribution in the direction of the failed bar axis.

So, e.g., during three-point bending with a reduced arm for the applied bending load, bending forces and parameters for the crushed area a increase, as a result of which the bending moment curve takes a form corresponding to curve 1 (see Fig. 3a). Distribution of bending load in the crushed area decreases the greatest bending moment, therefore, a somewhat larger force will be required for fracture, and consequently with larger values for crushed area parameters – i.e., with increasing axial spread of the crushed area caused by material hardness, applied force, or support shape – there will be a growth in bending load and the value of l_{ad} affecting the nature of fracture and blank quality. Similar results will occur in changing from three-point to four-point bending (see Fig. 3b). In this case the value of a will be governed by the distance between the furthest points of the crushed areas from the two supports.

By confining parts of the bar in sleeves which limit the deformation zone by radial compression adjacent to the plane proposed for fracture, the bending moment curve under conditions for linear load distribution under the sleeves corresponds to that given in Fig. 5; it depends on the amount of strain limitation determined by the level of radial compression and the point of load application. In the case of bending moment transmission from the sleeve with force transmission directly from the support to the bar (see Fig. 5a) the reduction in l_{ad} is greater, whereas contact of a support or pair of supports with the sleeves (see Fig. 5c) increases l_{ad} in comparison with three-point bending, and this is reflected in a corresponding change in blank quality.

It should also be noted that any deviation from stress distribution symmetry both during loading and during failure causes crack deviation from the proposed fracture plane. Three-point bending with unequal applied bending load arms (Fig. 6a) causes displacement of the plane corresponding to greatest bending, and consequently the greatest bending stress to a value

TABLE 1. Test Results for Steel ShKh15

Loading scheme	$l_1=l_2$, cm	l_{ad}, cm	P, kgf	$\frac{l_{ad}}{l}$	h_t, cm	$D-h_t$, cm	B, cm	$\sqrt{\frac{l_{ad}}{IB(D-h_t)l}}$	τ'', kgf/mm
Single support (D_{su} = 40 mm)	1,5	1,5	63000	1	0,75	2,25	2,6	0,207	23,6
					1,5	1,5	3	0,237	26,9
					2,25	0,75	2,6	0,359	41
	3	3	44000	1	0,75	2,25	2,6	0,207	33,1
					1,5	1,5	3	0,237	37,8
					2,25	0,75	2,6	0,359	57,6
Single support (flat support, a = 10 mm)	6	6	28000	1	0,75	2,25	2,6	0,207	42
					1,5	1,5	3	0,237	48
					2,25	0,75	2,6	0,359	73
	3	4	44000	$\frac{4}{3}$	0,75	2,25	2,6	0,223	47,4
					1,5	1,5	3	0,256	54,5
					2,25	0,75	2,6	0,388	82,8
Double support	3	5	4400	$\frac{5}{3}$	0,75	2,25	2,6	0,267	70,6
					1,5	1,5	3	0,306	81
					2,25	0,75	2,6	0,463	125
Single support in sleeves (loaded through a sleeve; see Fig. 5a) P_3 = 6000 kgf	6	5,15	28000	0,86	0,75	2,25	2,6	0,192	33,5
					1,5	1,5	3	0,219	38,2
					2,25	0,75	2,6	0,332	58
P_3 = 12,000 kgf	6	4,8	28000	0,8	0,75	2,25	2,6	0,185	30
					1,5	1,5	3	0,211	34,3
					2,25	0,75	2,6	0,32	52

$$\Delta l = k_2\left(\sqrt{\frac{l_1(l_1+2l_2)}{3}} - \frac{l_1+l_2}{2}\right), \tag{16}$$

where k_2 = 0.6 to 0.8 is a coefficient depending on material and notch parameters.

A similar result was obtained with deviation of the notch plane from the plane of support symmetry by a value of Δl. Since a crack tries to enter the zone of greatest stress, and in the precritical stage of development there are large tangential stresses τ'' on the side of the largest arm, crack deviation towards the greatest arm is maintained at all stages of failure. With asymmetric conditions for bar strain limitation (Fig. 6b) the stress curve is also distorted, as a result of which $l_{ad_1} < l_{ad_2}$, and the maximum value of bending moment is displaced towards the sleeve. In any case a crack at the initial stage of failure will try to enter the zone of greatest bending stress, and in the precritical stage with a sufficient level of tangential stresses it tends towards the direction of τ''.

The stress distribution curves considered above relate to smooth bar bending. Under notched conditions or with a growing crack the bending stress gradient increases in accordance with the stress concentration factor, which may be considered as an amendment of l_{ad}.

In accordance with the foregoing a study was made of single-support, double-support, and cantilever schemes for breaking steels ShKh15 and 45 (ϕ30 mm) on supports of different dimensions and shapes with various conditions for limiting strain by rigid sleeves and also with different adduced applied bending load arms. Cylindrical support radii were selected in the range 10-100 mm, and the distance between supports with four-point bending was in the range 5-25 mm. Sleeve length was 60 mm and the force applied was 6000-12,000 kgf. The value of the applied bending moment arm was selected in the range l = 0.5-3. As can be seen from Fig. 7 bending load and the axial extent of the crushed area decrease with increasing applied bending load arm, whereas there is an increase in the value of δ for greatest crack deviation from the notch plane caused by an increase in tangential stresses τ''. Deformation of a bar in rigid sleeves under stable uniform conditions decreases the value of δ (Fig. 8) and the greatest reduction occurs by bending with the scheme shown in Fig. 5a. Calculation of τ'' for 30-mm-diameter steel ShKh15 (μ = 0.3; I = 3.98 cm; k_1 = 0.111) at three points of the section with different loading schemes is given in Table 1.

Thus, data obtained by experimental study of the process for breaking rolled steel into blanks confirms with sufficient accuracy the results of loading scheme analysis, which in turn makes it possible to formulate a series of important practical recommendations. In particular, by breaking metal with a single-support scheme the quality of blanks obtained is markedly better than by breaking with a two-support scheme. The applied bending load arms should be 0.7-1.0 times the bar diameter, and the optimum shape of the curve is a cylinder with radius 0.8-1.2 times the diameter. Improved quality for breaking blanks is facilitated by reducing the applied loading arm and creating conditions limiting metal strain in areas adjacent to the break plane. With an increase in applied load asymmetry during fracture of a bar by bending, blank quality is reduced due to considerable deviation by the developing crack from the proposed fracture plane.

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TEST PROCEDURE WITH FOUR-POINT LOADING

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UDC 620.174+666.76.01+621.48

Mechanical testing by so-called four-point loading has been carried out for a long time [1], and in recent years the properties of crack-resistant ceramics, refractories, glass, graphite, concrete, and composites based on these materials have been studied under such conditions. In spite of this, changing requirements for the level and informativity of test results have continued to stimulate work on existing procedures and the creation of new study methods for this subject.

Four-point loading is attractive both for the possibility of collecting extensive information about material behavior under load, and the simplicity of its practical accomplishment. Even so, for strength determination the engineering realization of this loading is quite complicated if reliable experimental information is required. This is due to the fact that the expected stress–strain state of the gauge length corresponding to pure bending may be markedly disrupted due to uncontrolled rubbing and even specimen gripping or support rotation, unequal load distribution between points of application, etc. [2]. Stiffness of the loading system [3] and other factors may affect the reliability of results.

Although solution of problems associated with four-point loading has achieved some success, all the same (particularly in Soviet practice) there is no procedure which completely satisfies the requirements of experimenters. Therefore, work was performed on further improvement of test procedures connected with the use of four-point loading. In particular, a new construction of support was developed, and a rigid sensitive force meter designed to test slowly deforming modern structural materials was developed. In addition, a procedure was put into practice for studying precritical crack growth under these loading conditions.

The first variation of support created for a universal Instron machine (model TT-K), TsD-4, and RM-101 machine was fitted with mobile loading and intermediate rollers which provided rotation of support pads and facilitated specimen self-setting, and it was basically similar to the support described in [4]. Its satisfactory operation was apparent during tests on quite large specimens (8 × 12 × 100 mm and larger). Several

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