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COMPOSITE METAL AND PLASTIC PRODUCTION EQUIPMENT (TOOLING)[1]

by

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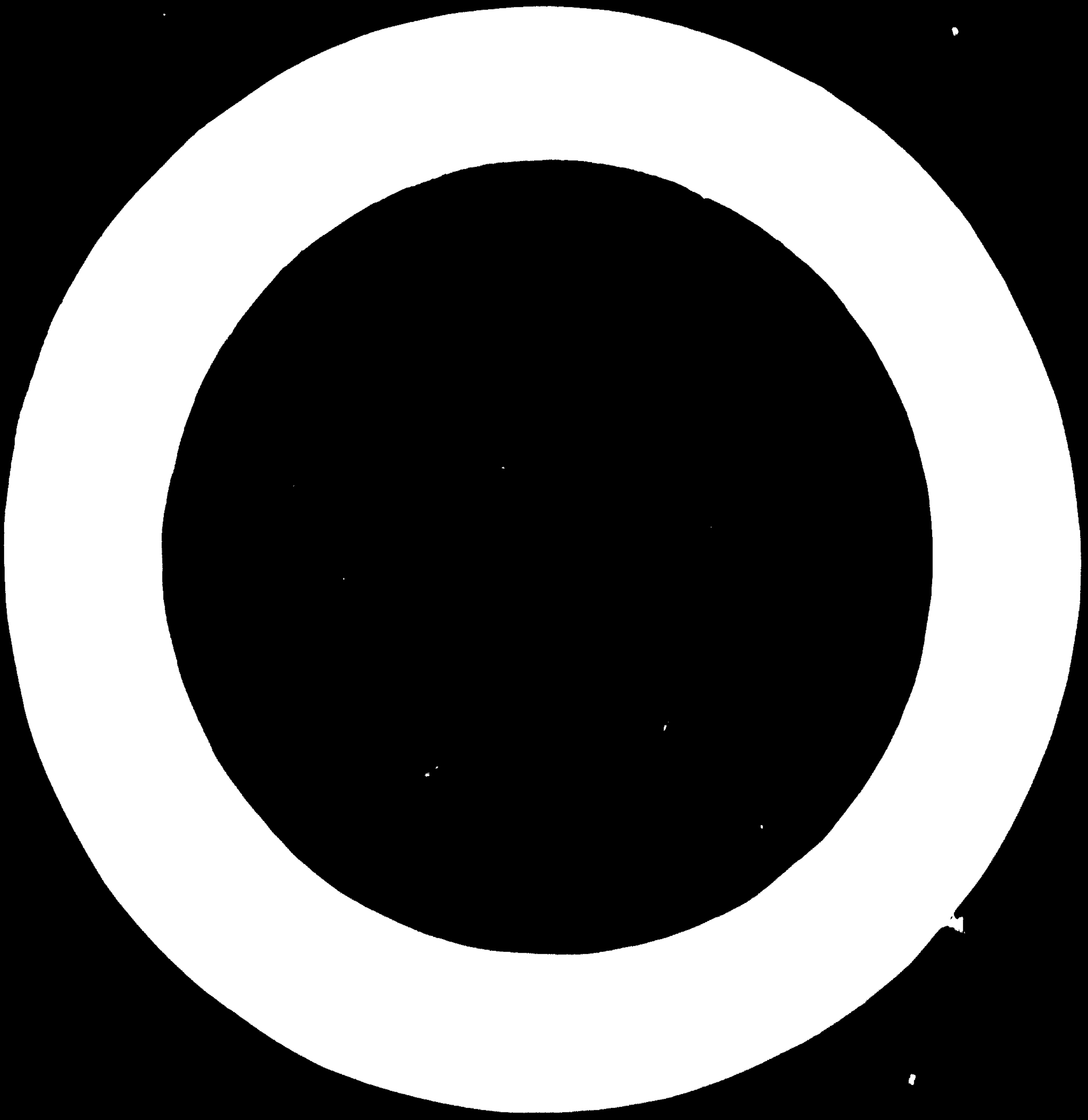
[1] The views and opinions expressed in this paper are those of the author and do not necessarily reflect the views of the secretariat of UNIDO.



The use of plastics for the manufacture of production equipment (tooling) of all kinds has opened up immense prospects for increasing the speed of the preparatory phases of production. This new trend not only makes it possible to speed up preparations for the manufacture of production equipment but also facilitates progress in advanced high-productivity methods of series production. It is particularly advantageous to use plastics in those branches of machine construction in which, owing to the smallness of the series and the frequency with which the products are changed, less sturdy but more rapidly and easily manufactured production equipment is advantageous. Although equipment of this type is less durable than that made of metal, it none the less has definite advantages. The replacement of metal by plastics results in savings of money and of materials that are in short supply. Production equipment made of plastic is considerably lighter and cheaper. In some cases, by using plastics, production equipment can be manufactured eight to ten times more rapidly and at four to five times less cost. Moreover, manufacturing techniques are simpler and more effective as a result. The manufacture of production equipment from plastics calls for less complicated tools and less highly skilled workers.

Plastics may be used in the manufacture of drawing and bending dies, machine-tool assembly and checking jigs, patterns, gauges, certain types of fitting instruments, models, core boxes and moulds.

Components for production equipment may be made from various artificial resins. However, not all of these resins possess the necessary mechanical properties or are suitable for one-off or small-series production. Plastics cannot be considered the ideal replacement for metals in all cases. When selecting plastics as construction materials, account must be taken not only of their physical and mechanical properties but also of the factors affecting them.

Extensive use is now being made in Soviet industry of ED-5, ED-6, E-40 and other epoxy resins for the manufacture of production equipment for the most varied functions. Epoxy compounds, which consist of resin, hardener, plasticizer and filler, possess good casting properties, do not give off volatile products in hardening, and in many cases harden at room temperature (16-20°C) without the use of pressure.

The hardened compounds are non-toxic and have quite high mechanical and operational properties. Their low shrinkage enables them to be used to make accurate castings of complicated shape. Castings made from them do not display distortion or suface or interior cracks, and they have good resistance to lubricants and coolants.

Epoxy resins adhere well to metals and to such non-metallic materials as plastics, wood, ceramics, porcelain and glass. In selecting the type of resin to use, it must be borne in mind that the mechanical strength of a compound prepared from ED-6 or E-40 resin is 10-15 per cent greater than that of a compound, otherwise of the same composition, prepared from ED-5 resin. Compounds made from ED-5 resin have better working properties, however.

The most commonly used hardeners are amines (polyethylene polyamine, ethylene diamine, hexamethylene diamine, or still residues of hexamethylene diamine) or basic organic acid anhydrides (maleic and phthalic acids). The first group of hardeners is used for cold hardening at a temperature of 16-20°C, and the hardening process lasts not less than 24 hours. The second group of hardeners is used for hot hardening at a temperature of 150-160°C. These hardeners are introduced into the resin in the melted state: maleic anhydride at a temperature of 60°C, and phthalic anhydride at a temperature of 130°C.

The amount of hardener used in compounds must be selected on the basis of experience, but the following amounts can be recommended per 100 parts of resin by weight: polyethylene polyamine 8-10 parts by weight; hexamethylene diamine (HMD) 10-15 parts by weight; still residues of HMD 20-25 parts by weight; maleic anhydride 30-41 parts by weight, and phthalic anhydride 45-61 parts by weight. In order to reduce the brittleness and increase the impact strength of the hardened castings, a plasticizer is mixed into the epoxy compound.

Depending on the purpose and the nature of operation of the production equipment which is to be made, and bearing in mind the properties of the epoxy compound, it is recommended, by way of example, that the following amounts of plasticizer be added to each 100 parts by weight of resin: dibutylphthalate 10-25 parts by weight, or liquid thiokol 15-30 parts by weight.

Fillers are used to give special properties to the compound and to reduce the cost of equipment made from it. They are of two types: powder fillers and fibre fillers. The most widely used powder fillers are iron powder, aluminium oxide, marshallite, quartz flour, graphite, talc, gypsum, cement, iron oxide, metal filings and aluminium powder.

In recent years, a wide use has come to be made of acrylic resin-based plastics (based on AST-T and TSh resins) for the manufacture of such production equipment as cradles, master forms, templates, drilling jigs, form blocks, core boxes, patterns and dies.

The following table gives the physical and mechanical properties of plastics based on epoxy and acrylic resins.

Physical and mechanical properties of plastics

Property:	Epoxy resin without filler	Epoxy resin with filler	Acrylic AST/T	Plastics: TSh
Density, kg/m^3(x 10^3):	1.15-1.25	up to 2.3	1.16-1.2	1.16-1.2
Strength, N/m^2(x 10^2):				
Tensile strength:	600-800	750-850	350-500	300-450
Compressive strength:	1300	1500	1200-1600	1000-1290
Bending strength:	900-1200	700-1000	800-1200	700-800
Brinell hardness:	10-12	25-30	13-19	12-15
Specific impact strength, NM/m^2(x 10^3):	3-7	8.5	8-12	12-15
Coefficient of linear expansion per degree centigrade (x 10):	6.0	2.0	-	-
Moisture absorption in 24 hours, per cent:	0.3	-	2.0	0.15
Shrinkage, per cent:	up to 2.3	0.03-0.4	0.4	0.3

In the design and production of machine-tool jigs, plastics are used mainly to make drilling jigs (of small dimensions), to mould jig bushings, to make cradles and certain types of body components, and to cement separate equipment parts together.

In order to speed up the production of equipment, a method has been devised for the manufacture of jigs by casting in disposable moulds using master metal parts as cores [1] [2].

This method considerably reduces or completely eliminates the need for subsequent machining.

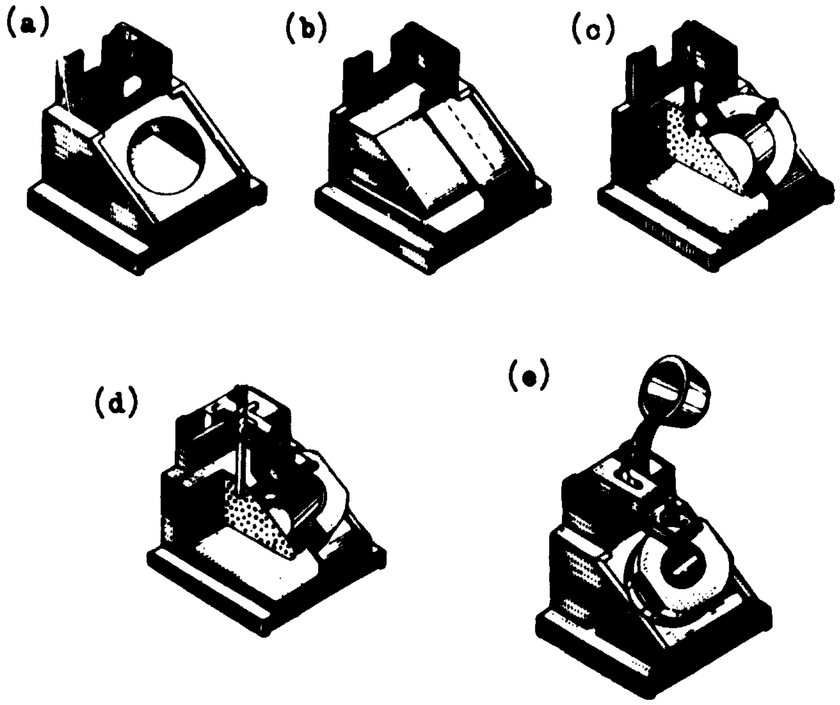
In essence, the method is as follows: the basic and auxiliary components, together with previously assembled units of the jigs, are placed on a layout block. The appropriate position for each part (supports, clamping devices, guides, etc.) in relation to the others is determined from the master (model) workpiece or from the assembly drawings for the jig. For this purpose, the parts are offered up to the master model of the workpiece to be machined and are then fixed in place on the layout block. The parts may be positioned and fixed by wiring, cementing, with the help of plasticine, with screw-clamps, or by other means. When the position of the parts has been checked, a cardboard or sheet iron mould in the shape of the jig body is prepared and placed on the layout block. Any gaps between the mould and the layout block are filled up with plasticine. The mould is then filled with epoxy compound and the jig is ready (assembled). If the uses of the jig are such that it requires a stronger body, the necessary metal reinforcements (frames, strengtheners, rods, etc.) will have to be set up on the block before the cardboard form is placed in position.

This method of jig-making thus comprises two stages: the preparation of the framework of the jig and the jig's subsequent assembly. If the use of the jig necessitates dismantling of its separate parts, the surfaces submerged in the plastic must be coated with a separating agent. Thus, for example, threaded pins and screws can be unscrewed from the plastic if their threaded surfaces are previously coated with such a separating agent.

Figure 1 shows the process for the manufacture of a special jig by the new method. The labour involved in the preparation of this jig is seven to ten times less than it would normally be. In normal circumstances, the manufacture of drilling jigs involves the boring of very accurately located holes. This process is considerably simplified and speeded up if very accurately set out jig bushes are cast in plastic.

Figure 1

Stages in the preparation of a drilling jig



a - Preparation of the cardboard mould; b - Fitting of the plasticine core; c and d - Setting of the jig bush to fit the master part; e - Pouring of the moulding compound.

Normal and drilling jigs incorporating very accurately located bushes can be designed and made in accordance with two systems.

In one of these systems, the jig plate is made of steel. In the other system, it is made of epoxy compound by building up in a mould successive layers of glass fibre fabric which may incorporate appropriate strengthening members when it is necessary to increase the rigidity of the jig, conduct away heat, and reduce shrinkage. Both processes for making jigs can be divided into two stages: the laying out and fastening of the bushes a very accurately determined distance apart, and the preparation of the plate for the jig. The bushes can be laid out either on marking-out plates or by using universal marking-off devices. The bushes are fixed in place with quick-hardening adhesive or on a magnetic block. After all the bushes have been placed in position, a steel plate of suitable thickness is mounted on them. The edge surfaces of this plate, on which the location of the axes of the bushes depends, must be accurately and smoothly machined. Before it is placed on the bushes, the plate is already bored to a normal degree of precision (of the order of 0.25mm) with holes whose position corresponds to that of the bushes and whose diameter is 2-4mm greater than the outside diameter of the bushes. Epoxy compound is then poured into the gap between the bushes and the walls of the holes. After epoxy compound has hardened, the distances between the centres of the bushes are checked by means of plug gauges inserted into the jig bushes and gauge blocks.

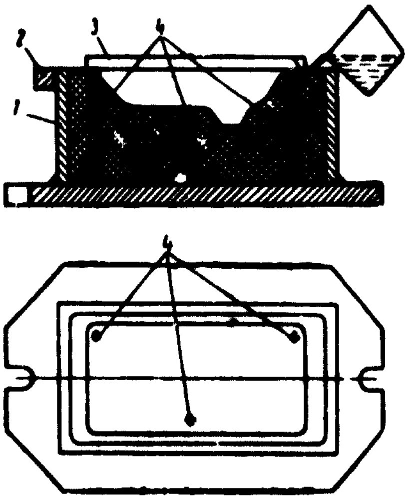
When a drilling jig is made of epoxy compound by lamination, a mould must be prepared and filled with compound after the bushes have been located in place by the methods described above. The mould can be made of metal or cardboard sections of appropriate shape. The accuracy of the distance between centres of the jig bushes cast in epoxy compound in a steel plate depends on the accuracy with which they were originally set out; if a plastic jig plate is used, then there may be a deviation in accuracy of the order of 0.1mm per 200mm of length (if a frame consisting of metal rods running in the direction of the critical dimension is used). Experiments have shown that there is no deterioration, in the course of operation, in the accuracy of the mutual location of jig bushes cast with epoxy compound in a steel plate. No turning of the bushes was observed during continuous drilling of steel workpieces without cooling (diameter of holes drilled: 10mm, depth of holes: 50mm, feed: 0.1mm/revolution, number of revolutions: 208 rev/min, drills used: type P18 steel drills, gap between bushes and walls: 2mm). In practice, in series production conditions the drilling of holes is not a continuous process: there are considerable intervals between drilling operations, and the temperature in the area of the plastic layer will not exceed 25-28°C.

In modern machine construction there are a number of workpieces of complex shape made by casting or stamping (levers, angle pieces, T-pieces, cross-pieces, tap bodies, brackets, and the like) which are very difficult and inconvenient to machine in all-purpose jigs. Special jigs have to be constructed for them, and this entails a great wastage of time and labour. Such jigs are considerably easier and cheaper to produce if the mounting units are made of plastic. In such cases these mounting units of the jig (cradles) are in the form of female impressions or depressions corresponding exactly to the surface of the workpiece. The entire surface of the workpiece to be machined is fitted into this depression (cradle).

A standardized steel body is used to contain the cradle. One version of the process for making cradles is shown in Fig. 2. The casting material used is epoxy compound, which has the advantage over other casting materials, such as low melting point alloys, of having a low coefficient of shrinkage.

Figure 2

Casting of the mounting surface (cradle) of a machine tool jig, using a master part as a moulding core



1 - Body; 2 - Mounting base plate; 3 - Master part; 4 - Supports.

When using an actual workpiece as a model for the preparation of cradle jigs, it is recommended that a carefully machined workpiece of maximum permissible dimensions should be used for this purpose.

In order to increase the ridigity and strength of such jigs, it is recommended that fibre fillers (such as glass fibre, asbestos, etc.) combined with a powder filler be used, and that the height of the casting in the frame should be kept as low as possible (i.e., the distance between the female impression and the body should be reduced).

In calculating the strength of cradle jigs, it is essential that the specific pressure on the bearing surface should be kept below 70-80 MN/m^2 (7-8 kg/mm^2), depending on the strength of the lining composition. It is wise to provide several depressions in the bottom surface of the cradle to collect chips which might fall in and upset the proper contact between the workpieces and the cradle, thus leading to rejection of the machined part. In order to prevent edge contact between the workpiece and the cradle surface it is necessary to make bevels or chamfers on the upper surfaces of the cradle and to provide indentations at points where the workpieces may bear traces of the break line of the patterns and dies. In order to ensure adequate stability for workpieces in shallow cradles, sufficiently large angles of grip must be used.

Since the workpiece is mounted over its entire surface, the machining comes within the fourth or fifth classes of precision. In order to increase the precision of machining, it is necessary to mount the workpieces in cradles manufactured by high-precision methods (precision pressure casting, casting with melted cores, shell-mould casting, metal-die casting, closed-die forging, etc.).

A high quality epoxy compound with good wear resistance and strength must be used to line the working surfaces of the cradle. Materials such as aluminium oxide, iron powder, marshallite, asbestos or graphite can be used as fillers. In order to obtain accurate and clean-surfaced castings, carefully made moulds must be used. When production equipment parts are being cast from plastics, however, the plastic casting shrinks during the process of polymerization, and this influences the accuracy of dimensions and shape of the parts thus manufactured.

One of the principal ways in which the accuracy of castings made from plastics can be improved is to modify the mould dimensions on the basis of experimentally established coefficients of shrinkage.

Effective use can be made, in the manufacture of production equipment, of epoxy resin-based adhesives, which give great strength of adhesion. Such epoxy resins give a tensile strength (under uniform load) of up to 60 MN/m^2 (600 kg/cm^2) and a shear strength of up to 35-50 MN/m^2 (350-500 kg/cm^2). Such adhesive compounds can be used to fix parts to cylindrical, conical, flat and other surfaces. In many cases, they can take the place of screw, pin, riveted, or keyed fixings and rivets set in under-sized holes. This makes it possible to simplify the design of jig components, reduce the number of fastening parts in them, and also reduce the degree of accuracy which must be observed in their manufacture. As a result, the manufacture of production equipment can be speeded up and the cost of such equipment reduced.

Moreover, when parts are fixed together with adhesive the units thus assembled are not distorted, as they might be if they were soldered or welded. Cemented joints have the property of absorbing vibration: an advantage which is particularly valuable in the case of machine tool jigs. Cemented joints work well under conditions of dynamic and variable loading, they stand up well to compression, shear and symmetrical tensile stress, but do not stand up well to tearing stresses (non-symmetrical tensile stress).

Among the drawbacks of cemented joints are their relatively low heat resistance (at temperatures over 90°C their strength falls off sharply) and their tendence to creep under prolonged heavy static loads (such as the forces developed in bolt tensioning).

The main steps in the assembly of jig components by the use of adhesive are:

(a) The preparation of the surfaces for cementing;
(b) The preparation of the adhesive, and
(c) The application of the adhesive and assembly of the parts.

It has been established on the basis of experiments that the surface roughness of the surfaces to be cemented together and the size of the gap between them have a significant influence on the strength of the resulting joint. The greatest shear strength of a cemented joint is obtained by machining the surfaces to be cemented together to a finish of $\nabla 4$-$\nabla 5$ (All-Union State Standard 2789-59), while the greatest tensile strength (under regular stress) is obtained by machining the surfaces to a finish of $\nabla 6$-$\nabla 7$ (All-Union State Standard 2789-59).

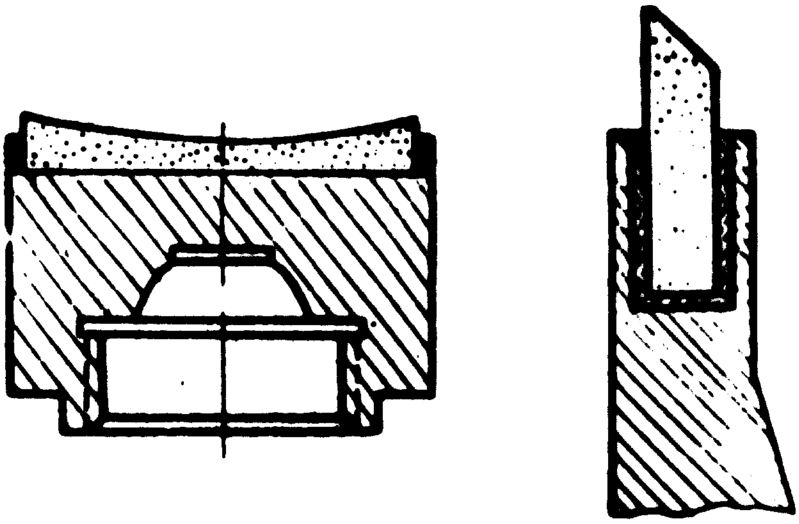
The strength depends on the size of the gap (the thickness of the film of adhesive). It is recommended that the gap should be between 0.05mm and 0.2mm. The necessary heating temperature and the setting time depend on the composition of the adhesive.

Adhesives based on epoxy resin have good resistance to the action of liquid coolants (emulsions, aqueous soda solutions, sulphurized machining oils, mineral and vegetable oils) used in metal machining. They do not swell, and lose practically none of their strength. Assemblies which are cemented together can easily be taken apart after local or general heating to 300-350°C.

Figure 3 shows adhesive-bonded blades and supports for centreless grinding machines. The blades and supports are tipped with strips of VK6M hard alloy fixed in place with epoxy adhesive (epoxy resin 100 parts by weight, polyethylene polyamine 10 parts by weight). The hard alloy strips could not be fixed in place by other methods, such as welding, because of the great distortion which would be caused.

Figure 3

Adhesive bonding of supports and knives on a centreless grinding machine



In order to increase the strength of adhesive bonds, it is essential to reduce the stresses arising as a result of shrinkage of the adhesive and the action of higher temperatures during operation. While the film of adhesive is hardening, shrinkage takes place and causes internal stresses in the film. These stresses try to pull together the metal surfaces which are being cemented together, thus stretching the film of adhesive and reducing its strength.

Normal stresses in the adhesive film in a biascial stressed state can be expressed by the formula:

$$\sigma_{as} = \epsilon_a \frac{E_a}{1 - \mu_a} \qquad (1)$$

where ϵ_a is the relative elongation of the adhesive film under tension or compression (linear shrinkage Δ);

E_a is the modulus of elasticity of the adhesive, in kg/cm^2;

μ_a is the Poisson's ratio of the adhesive.

In operation, the adhesive may be exposed to temperatures which may generate stresses. In view of the thinness of the adhesive film, the normal stress can be considered as being the same throughout the cross-section of the film, and it can be calculated according to the formula:

$$\sigma_{at} = \Delta t \, (\alpha_a - \alpha_m) \frac{E_a}{1 - \mu_a} \qquad (2)$$

where Δt is the change in temperature of the adhesive;

α_a and α_m are the coefficients of linear expansion of the adhesive and the metal.

If we analyze formulae (1) and (2), the following conclusions may be drawn: the normal stresses can be reduced through reduction of the shrinkage (formula (1)) and reduction of the difference in the coefficients of linear expansion (formula (2)). This can be achieved by incorporating various filters in the adhesive.

If the composition of the adhesive includes several fillers, then formula (2) will have the following form:

$$\sigma_{at} = \Delta t \frac{E_a}{1 - \mu_a} \left(\frac{\alpha_r + C_1 \alpha_{f_1} + \ldots\ldots + C_n \alpha_{f_n}}{1 + C_1 + \ldots\ldots + C_n} - \alpha_m \right) \qquad (3)$$

where α_r is the coefficient of linear expansion of the adhesive without filler;

$\alpha_{f_1} \ldots\ldots \alpha_{f_n}$ are the coefficients of linear expansion of filler 1...n;

$C_1 \ldots\ldots C_n$ are the proportions by volume (with respect to the resin) of the fillers in the adhesive composition.

When an adhesive composition must be used in conditions where there are changes of temperature, it is essential to incorporate fillers with a low coefficient of linear expansion in the adhesive, while striving at the same time to achieve the following conditions:

$$\frac{\alpha_r + C_1 \alpha_{f_1} + \ldots\ldots C_n \alpha_{f_n}}{1 + C_1 + \ldots\ldots + C_n} \to \alpha_m \qquad (4)$$

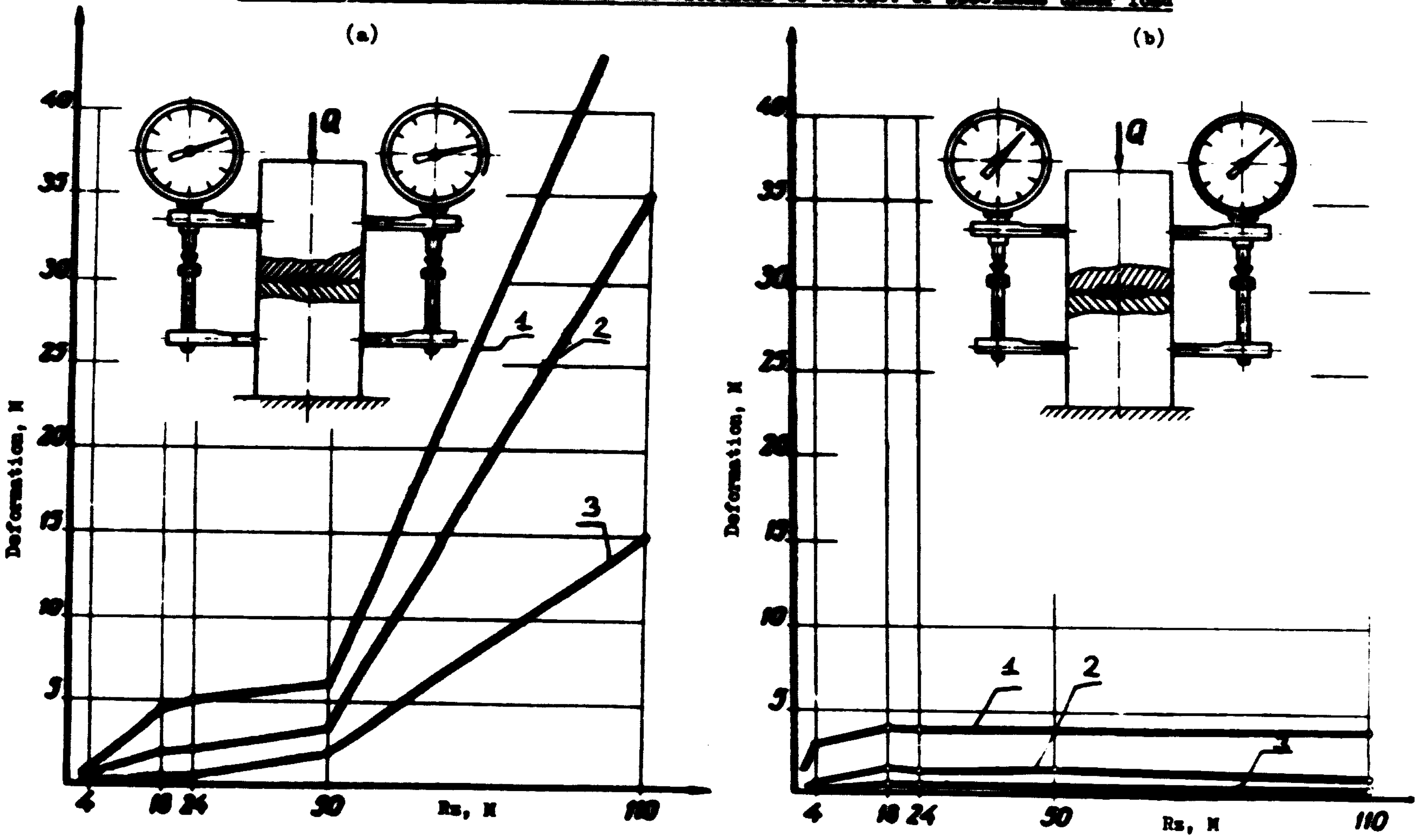
The best fillers to use are marshallite or quarts flour, which have the low coefficient of linear expansion of -0.5×10^{-6}.

The use of adhesive compounds makes it possible to increase the contact strength of joints. Experiments show that the contact strength of normal flat butt joints depends to a considerable extent on the roughness of the contact surfaces. The use of cemented joints, however, reduces contact deformation to the point where the contact strength of cemented joints, for a given adhesive composition, practically ceases to depend on their surface roughness (Figure 4). The experiments were carried out on face-turned specimens which were displaced out of centre during machining so that when placed face to face the grooves left by machining crossed each other.

It was noticed in the investigation that contact deformation depended also on the amount of filler (marshallite) used in the adhesive. The results of the investigation are given in Figure 5.

Figure 4

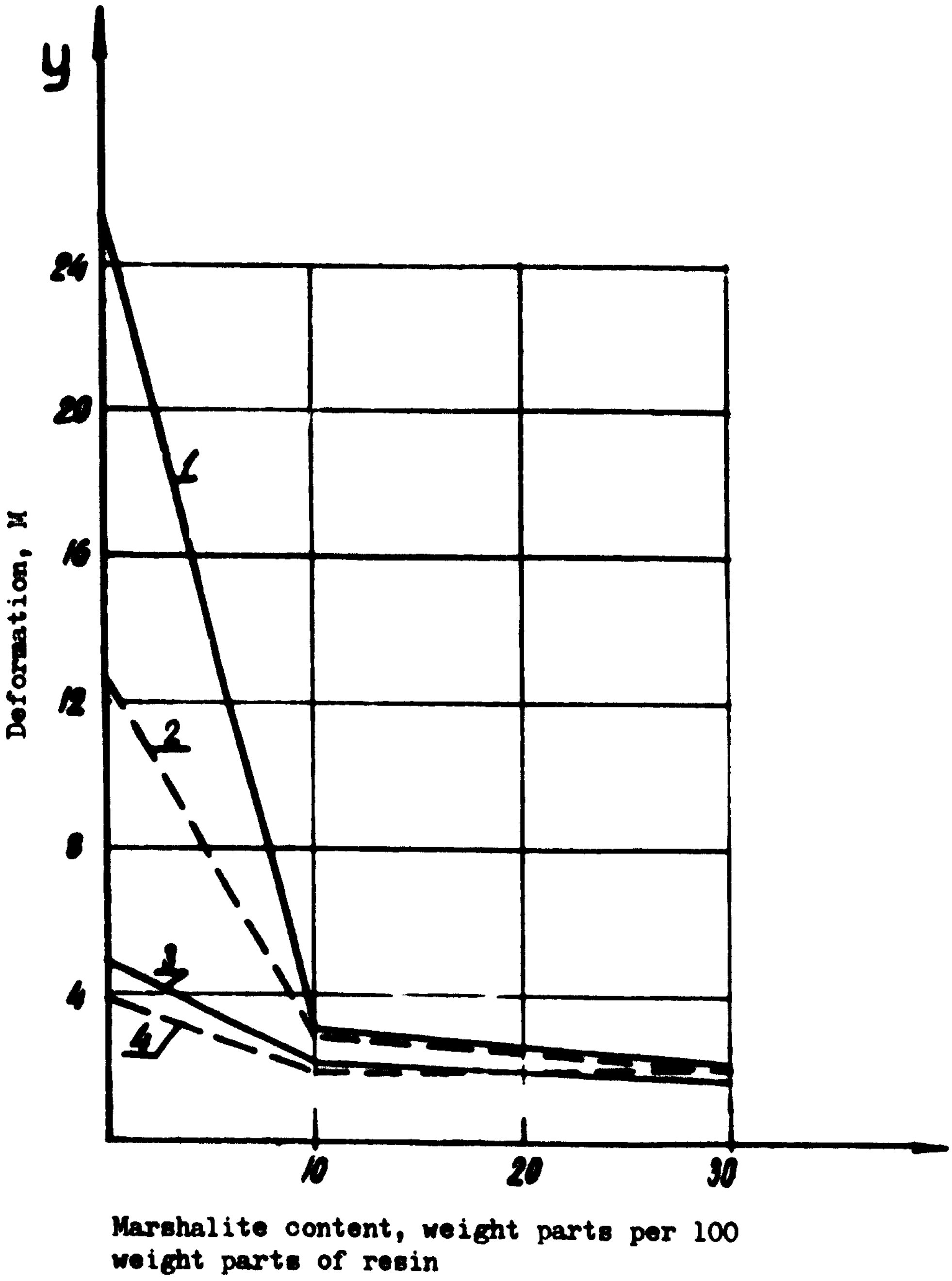
Influence of surface roughness on the closeness of contact of specimens under load



a - Without adhesive; b - With adhesive. 1 - Q = 12.5 MN/m^2 = 125 kg/cm^2; 2 - Q = 5.4 MN/m^2 = 54 kg/cm^2; 3 - Q = 1.8 MN/m^2 = 18 kg/cm^2.

Figure 5

Influence of filler content of adhesive compositions on the contact deformation of joints under load



Surface finish: 1 - ∇2; 2 - ∇3; 3 - ∇4; 4 - ∇5. Load applied: 7 MN/m^2 (70 kg/cm^2).

The use of marshallite in the adhesive compound considerably reduces contact deformation for rough surfaces, and with a marshallite content of 30 parts by weight the contact deformation becomes identical for surfaces with roughness ranging from V2 to V5. This fact enables the surface finish requirements for jig parts to be reduced, and, if necessary, adhesive or plastic films to be used as compensators in the assembly of jigs. Particularly great advantages are gained by the use of adhesive film in jigs with a large number of butt joints. Figure 6 gives the results of an investigation of the influence of vibration on contact strength for designs consisting of three flat butt joints. As may be seen from the graph in the figure, the strength of the adhesive joints is considerably higher than that of the three joints held together with bolts. This is explained by the fact that the adhesive fills up the very small surface inequalities, thus preventing the crumbling of these small inequalities and the distortion of the plates. Under the influence of prolonged vibration, the rigidity of the bolted joints falls off somewhat because of weakening of the tightening force, while the rigidity of the adhesive joint remains at the same level.

The technical and economic advantages of using plastics in the manufacture of dies result from the shorter time required for production preparations and the lower manufacturing costs.

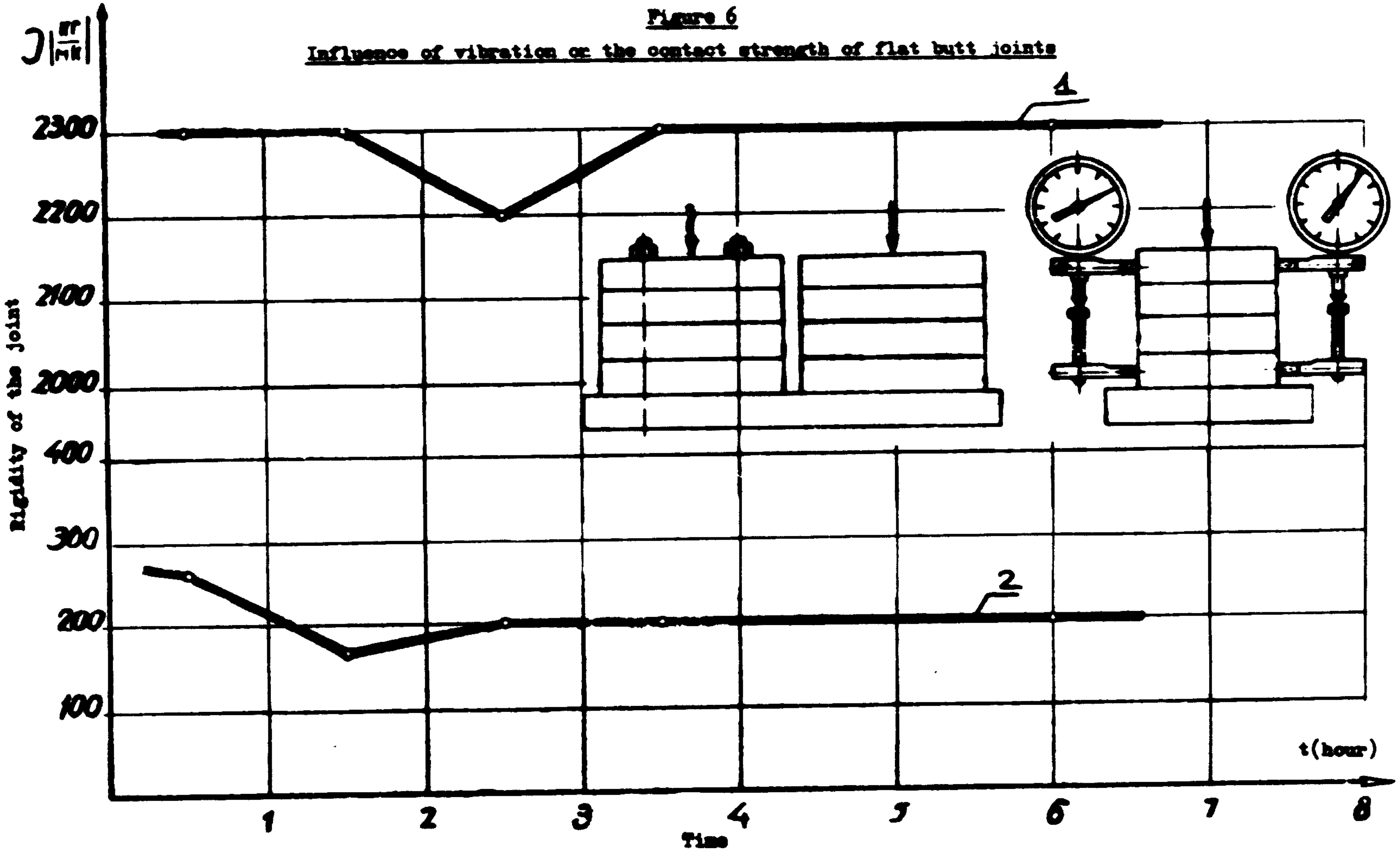
The manufacture of dies from plastics eliminates the need for profile machining and metal finishing work, which accounts for 50 per cent of the total labour expended on the manufacture of metal dies. Plastics can be used to make the working parts of all types of dies except the cutting components of blanking dies.

There are various ways of making the shaping parts of dies (the punches, the matrices and the clamping elements) from plastics, including casting in moulds, pressing, etc. At present the most widely used method of preparing the shaping parts of dies from compounds based on epoxy resins is casting.

Various types of designs have been used for drawing dies: (1) An outer layer of epoxy compound on a stabilized sand base; (2) An outer layer of epoxy compound on a wooden centre; (3) A cast iron centre with an outer coating of epoxy compound; (4) An outer coating of epoxy compound on a centre consisting

Figure 6

Influence of vibration on the contact strength of flat butt joints



1 - Fastening by means of adhesive (3 joints); 2 - Fastening by means of bolts (3 joints).

of a welded metal frame; (5) Plastic over a steel plate. The first four types of design are used for large punches, while the third and fourth varieties offer a high degree of durability. The last type of construction is used for small punches, and in order to increase their strength it is recommended that the shaping inserts of the die and punch should be cast in welded metal casings.

The use of a metal base has the following advantages: (1) It enables expensive resin to be saved, since only a thin layer of plastic (12-15 mm thick) is applied; (2) The rigidity of the punch is increased (this is very important for the stability of the punch and for the accuracy of the parts punched); (3) The punch is more durable.

Dies with a plastic coating can be made from wooden models or from a master specimen part. The second procedure is simpler. A special model, made by hand from sheet steel of the same thickness as the part to be punched, is used as the master specimen part for shaping the profile of the working surface. Figure 7 shows the various stages in the manufacture of the die.

To form the sliding surfaces of the die guides it is advisable to use fast-hardening AST-T plastic and TSh Styracryl.

Plastic dies for sheet stamping are used in many small-scale machine construction plants. They are 2-5 times less costly in labour and material than metal punches. To increase the sturdiness of the dies, the plastic shaping surface is nowadays subjected to a metallization process.

In drawing, the most heavily stressed areas are the radiused surfaces of the punch or die [3]. The following compressive stresses are set up on these radiused surfaces of the die:

$$\sigma_{com} = \sigma_{\rho\ max} \frac{s}{r_d}$$

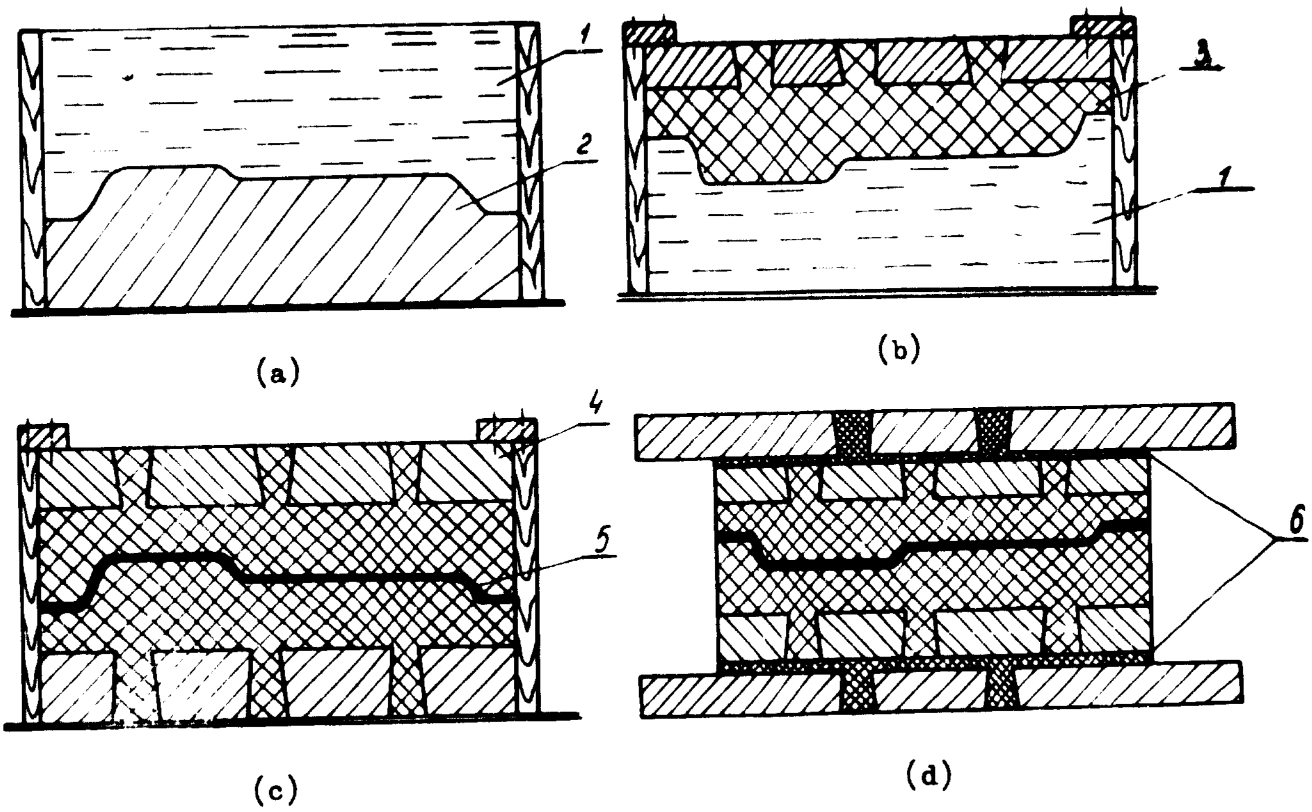
Where $\sigma_{\rho\ max}$ is the maximum value of the tensile force on the most heavily stressed section, in N/m^2 (kg/mm^2);

s is the thickness of the material being worked, in mm; and

r_d is the radius of die curvature, in mm.

Figure 7

Sequence of operations in the preparation of a plastic-faced die



(a) (b)

(c) (d)

1 - Plaster; 2 - Master model; 3 - Plastic facing; 4 - Bottom plate;
5 - Foil; 6 - Levelling layer.

In the case of drawing with a pressure pad,

$$\sigma_{\rho\ \max} = \sigma_y \left(\ln\frac{R_o}{R_c} + \frac{\mu Q}{\pi R_o s \sigma_y} - \frac{s}{2r_d + s} \right) (1 + 1.6\mu) \qquad (5)$$

In the case of drawing where a pressure pad is not used.

$$\sigma_{\rho\ \max} = \sigma_y \left(\ln\frac{R_o}{R_c} + \frac{s}{2r_d + s} \right) (1 + 1.6\mu) \qquad (6)$$

Where σ_y is the yield point of the material being stamped, in N/m^2 (kg/mm^2);

s is the thickness of the material being worked, in mm;

μ is the Poisson's ratio for the material being worked;

r_d is the radius of the curvature of the die, in mm;

Q is the load applied by the pressure pad, in N(kg);

R_c is the radius of the outer surface of the part being worked (measured across the flanges), in mm;

R_c is the radius of the most heavily stressed section, (the critical section), in mm.

Thus, the stresses depend on the thickness of the material being stamped, s, on the type of material being stamped σ_y, and on the radius of curvature of the die r_d. When designing plastic die sets, the radii of curvature must therefore be large (not less than 4 mm).

To increase the durability of the plastic coating in the stamping process, metal inserts will be needed at the points of greatest stress, such as hollow chamfers. For this purpose, provision should be made for keying devices such as holes, recesses, grooves, ribs, ridges, etc.

Before pouring the plastic it is advisable to make keying holes which will fill up with compound during pouring and thus strengthen the grip of the plastic coating. The die and punch can be fastened to the plate by means of bolts cast in the plastic.

Rigidity is a basic factor in ensuring the efficiency of dies, jigs, cradles and other types of equipment. It can be achieved by careful selection of the composition of the compound, by using various specific types of fillers, and also by reinforcing with metal components. For this purpose, dies and seatings are cast on a metal base or over metal frames. In such cases, however, residual stresses can occur in the metal and plastic structures as the result of contraction of the plastic and differences in the coefficients of linear expansion during polymerization.

These residual stresses will be additional to the normal working stresses, which they can increase or decrease. Research has shown that residual stress in composite metal and plastic structures can, in many cases, be quite considerable and result in damage to the plastic even without the effect of working loads.

A number of researchers [4] [5] have demonstrated that shrinkage of the epoxy compound largely depends on the hardening time, the composition of the compound and the temperature at which hardening takes place. For example a composition of resin, hardener and plasticizer has a shrinkage of 0.3 per cent, while the same composition with 200 parts (by weight) of iron powder has a shrinkage of 0.18 per cent.

Any shrinkage will lead to a state of stress in metal-reinforced plastic structures. Such stress is due to the fact that the force of adhesion of the plastic to the metal base impedes shrinkage.

The pattern of occurrence of residual stress in metal-reinforced plastic structures is similarly influenced by temperature changes. The coefficients of linear expansion of epoxy compounds are 2 to 4 times higher than the coefficient of linear expansion of steel; consequently, when epoxy compound is cast over a steel plate or steel frame residual stress occurs with the changes in temperature. These stresses are particularly great when hot-hardening compounds are used and when hardening takes place at a temperature of 120 to 160°C, followed by cooling to room temperature.

Let us now consider the determination of the residual stresses caused by temperature variations in certain designs of composite metal and plastic production equipment. Designs of production equipment which consist of a rectangular metal base whose length is considerably greater than its width and which is covered with a layer of plastics (such as templates, master-patterns and dies) can be treated as two-layers strips for purpose of calculation. When there are temperature changes, such as for example, cooling of the equipment, the layer of plastics will attempt to shorten itself by an amount $\Delta t\ (\alpha_1 - \alpha_2)$ which will be greater than that of the metal base.

This will cause the following stresses to arise in the plastic layer:

$$\sigma_1 = E_1[\varepsilon_0 - \frac{z}{\rho} - \Delta t(\alpha_1 - \alpha_2)] \qquad (7)$$

where $0 \leqslant z \leqslant h_1$.

The stresses in the metal base will be:

$$\sigma_2 = E_2 \left(\varepsilon_o + \frac{z}{\rho}\right)$$

where $-h_2 \leq z \leq 0$;

E_1, E_2	are the moduli of elasticity of the plastic and the metal, respectively;
ε_o	is the deformation of the boundary surface of the metal and plastic;
ρ	is the curvature of the boundary surface of the metal and plastic;
Δt	is the temperature variation;
α_1, α_2	are the respective coefficients of linear expansion of the plastic and metal;
h_1, h_2	are the respective thicknesses of the layers of plastic and metal, and
z	is the co-ordinate of the section under consideration.

In order to determine ε_o and ρ let us construct the following equations:

$$\Sigma N = 0 \qquad \int_o^h \sigma_1 b dz + \int_{-h_2}^{o} \sigma_2 b dz = 0 \tag{9}$$

$$\Sigma M_{manuf.} = 0 \qquad \int_o^h \sigma_1 bzdz + \int_{-h_2}^{o} \sigma_2 bzds = 0 \tag{10}$$

By substituting the values σ_1 and σ_2 in this system of equations and proceeding to its solution we obtain:

$$\frac{1}{\rho} = \frac{6\Delta t\,(\alpha_1 - \alpha_2)}{\dfrac{(E_1h_1^2 - E_2^2h_2^2)^2}{E_1E_2h_1h_2(h_1 + h_2)} + 4(h_1 + h_2)} \tag{11}$$

$$\varepsilon_o = \frac{1}{E_1h_1 + E_2h_2}\left[\Delta t(\alpha_1 - \alpha_2)E_1h_1 - \frac{1}{2\rho}\,(E_1h_1^2 - E_2h_2^2)\right] \tag{12}$$

The functions thus obtained enable us to determine the residual stresses both in the plastic layer and in the metal layer, and with the aid of expression (11) we can determine the deviation of the surface shape, which is of great importance in the preparation of accurate master patterns and templates.

Analysis of equation (7) shows that the greatest residual stresses in the plastic arise at the boundary with the metal layer. The residual stresses vary linearly with depth. The greatest stresses in the plastic are tensile stresses at the boundary with the metal layer. At the outer surface of the plastic the stresses are smaller, and in the case of certain relationships between the thickness of the plastic and metal layers they may disappear completely. The greatest stresses in the metal are at its surface of contact with the plastic.

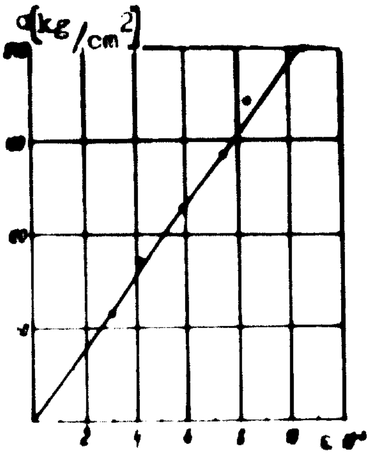
The stresses determined by the above methods diminish with the passage of time. This is due to the fact that in time the phenomenon of creep takes place in epoxy compound kept under load. An experiment was carried out on specimens made of such compound in order to determine its creep characteristics.

In short-duration tensile tests, (Figure 8), the modulus of elasticity was:

$$E = 2.3 \times 10^4 \text{kg/cm}^2 (\sigma_{\text{fail}} = 24 \text{ MN/m}^2 = 240 \text{kg/cm}^2, \ \varepsilon_{\text{fail}} = 10.4 \times 10^{-3}).$$

Figure 8

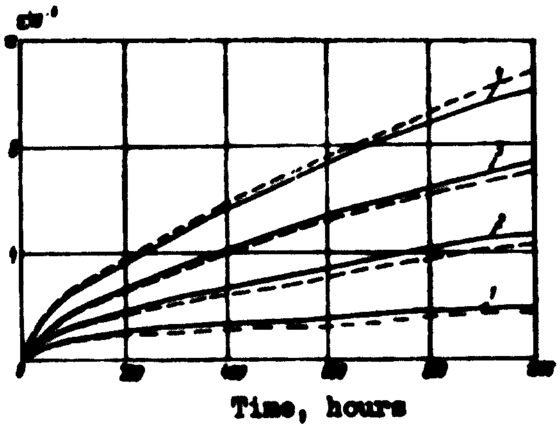
Tension diagram



In long-duration tensile tests, the loading rates were within the range 3-12 MN/m^2 (30-120 kg/cm^2). The creep characteristics were determined on the basis of 1,000 hour tests, and the creep curves are shown in Figure 9. At a load of 3 MN/m^2 (30 kg/cm^2) the creep was of a gradually diminishing nature, and the creep deformation after 1,000 hours was $\varepsilon_p = 2 \times 10^{-3}$. At a load of 12 MN/m^2 (120 kg/cm^2) the creep deformation was $\varepsilon_p = 10 \times 10^{-3}$.

Figure 9

Creep curves



1 - σ = 3 MN/m^2 = 30 kg/cm^2; 2 - σ = 6 MN/m^2 = 60 kg/cm^2; 3 - σ = 9 MN/m^2 =
90 kg/cm^2; 4 - σ 12 MN/m^2 = 120 kg/cm^2.

The relaxation tests lasted 500 hours, with initial stress levels of 9 and 6 MN/m^2 (90 and 60 kg/cm^2). Stress relaxation after this length of time amounted to about 50 per cent of the initial stress levels.

In order to determine by calculation the behaviour with time of parts made from a material under investigation, the applicability of the creep hypothesis to the material in question was investigated. Particular attention was devoted to:

the ageing hypothesis $\varepsilon_p = \Omega\sigma^n$ (13)

and the flow hypothesis $\dot{\varepsilon}_p = B\sigma^n$ (14)

where ε_p is the plastic deformation;

$\dot{\varepsilon}_p$ is the rate of plastic deformation;

σ is the stress;

n is the temperature-dependent creep index, and

B and Ω are time and temperature functions connected by the relationship:

$$\Omega \int_0^t B\,dt \tag{15}$$

The creep index n = 1.35 was determined from a graph showing the relationship between $\lg\frac{\sigma}{\sigma_{min}}$ and $\lg\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_{p\,min}}$ (Figure 10). Graphs of the function Ω used for calculations in cases of monoaxial strain are given in Figure 11 for both hypotheses. In Figure 9, the dotted line represents the theoretical creep curves, calculated for the values of Ω and n for each material.

Figure 10

Relation between stress and rate of creep

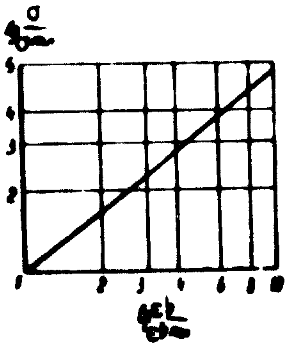
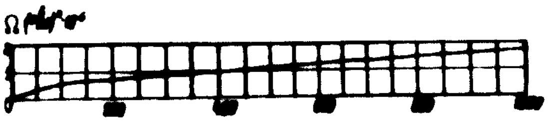


Figure 11

Graph for the function Ω $(cm^2/kg)^n \times 10^{-5}$



In order to determine the theoretical values for stress relaxation, the following relationships were used:

for the ageing hypothesis:

$$\sigma = \frac{\sigma_0}{(1 + nE\sigma_0^{n-1}\Omega)^{1/n}}; \tag{16}$$

for the flow hypothesis:

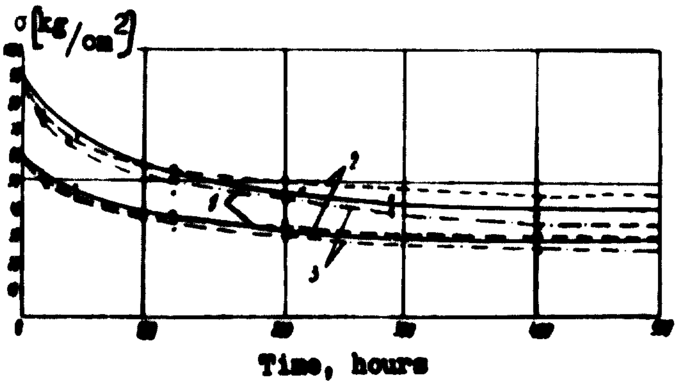
$$\sigma = \frac{\sigma_0}{[1 + (n - 1)E\sigma_0^{n-1}\Omega]^{1/n-1}} \tag{17}$$

where σ_0 is the initial stress.

Figure 12 shows the experimental and theoretical curves for stress relaxation. The correspondence of these curves indicates that the creep of parts made from a given material can be calculated from the equations given in paper [7].

Figure 12

Stress relaxation curves

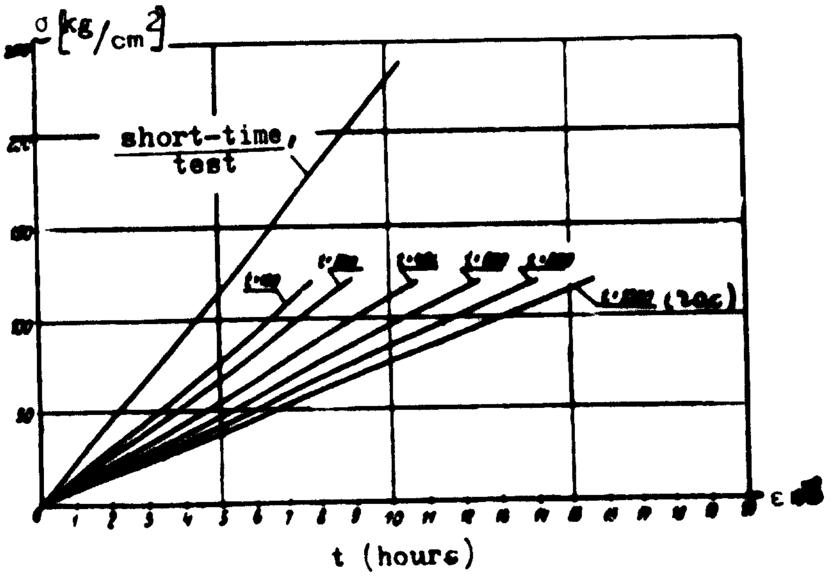


1 - Experimental curve; 2 - Valves calculated according to the aging hypothesis; 3 - Valves calculated according to the flow hypothesis.

The use of this method involves great difficulties of a mathetical nature, however. We will therefore propose another method of calculation.

A certain function $\sigma = f(\varepsilon)$ (Figure 13), based on the creep curves (Figure 9), exists for each moment of time t_1 and can be determined from the creep diagram.

Figure 13
Deformation curve for epoxy compound

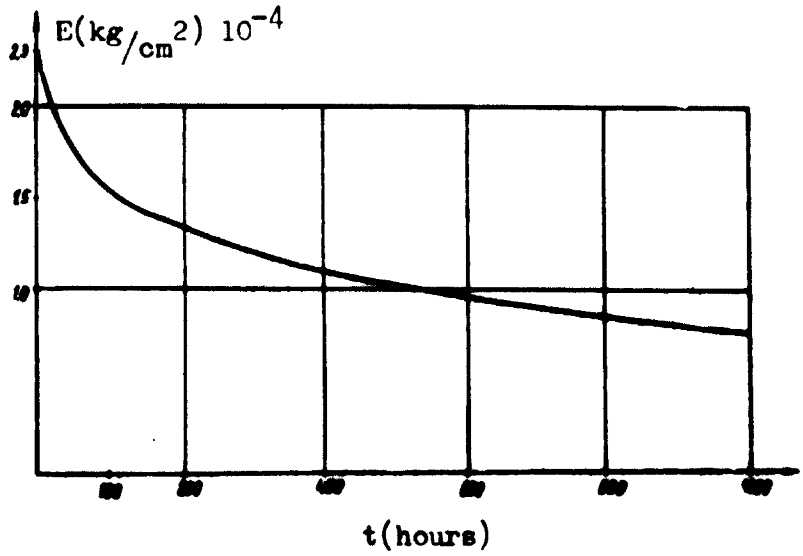


By approximating the deformation curves thus obtained to straight lines (the experiment shows that this is entirely permissible), the calculation can be reduced to a flexible analysis of the design, with subsequent substitution of the time-variable modulus of elasticity for the modulus of elasticity of the first type.

This time-variable modulus can be determined from the deformation diagram (Figure 13). A graph for variation of the modulus of elasticity with time is given in Figure 14.

Figure 14

Variation of the modulus of elasticity of epoxy compound with passage of time



Thus, the residual stresses caused by temperature deformations diminish with the passage of time, and their value can be determined by calculation through the method given above, with substitution of the modulus of elasticity taken from the diagram in Figure 14.

In determining the residual stresses caused by shrinkage of the compound in hardening, it is essential to bear in mind the fact that such shrinkage, particularly shrinkage during cold setting, takes place quite slowly, so that two processes are actually taking place at the same time: the process of the generation of residual stresses due to shrinkage, and the process of relaxation of these stresses.

The residual stresses can be calculated in this case also by the step-by-step method in accordance with relationships (7) and (8), substituting the deformation due to shrinkage Δ for the temperature deformation $\Delta t(\alpha_1 - \alpha_2)$, and taking into account stress relaxation.

Calculations made in accordance with these formulae show that the residual stresses set up through shrinkage may reach quite high levels, attaining as much as 10 MN/m^2 (100 kg/cm^2) of tensile stress. Where hot hardening is used, the residual stresses are considerably increased.

These residual stresses are algebraically added to the working stresses set up in the process of utilization of the equipment.

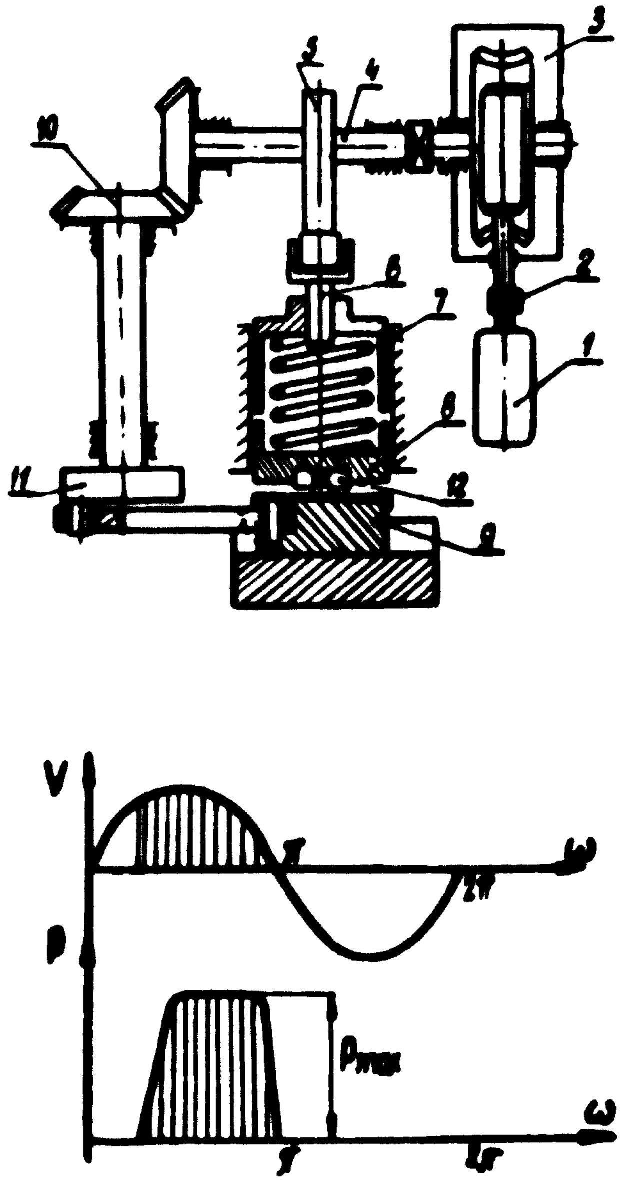
An important index of the serviceability of production equipment is its wear resistance, and this is particularly important in the operation of dies. In stamping, the working surfaces of the die become worn through the action of the high specific pressures to which they are subjected. The wear process on dies has been reproduced in model form on a special experimental apparatus (Figure 15) which fully reproduces the loading cycle taking place in die operation. This apparatus can exert loads on the test specimen within the range 5-30 MN/m^2 (50-300 kg/cm^2) and can at the same time drag a steel sheet across its surface.

Specimens of the compound under investigation were cast in metal casings. Wear was determined by weighing the specimens on analytical balances. In operation, the specimen and the metal sheet were lubricated with machine oil. Testing was carried out at the rate of 2,000 cycles per hour. In the course of the complete experimental process, each specimen was subjected to 12,000 test cycles. The results of the experiment are given in Figure 16. Analysis of the experimental data shows that wear on plastic dies operated under specific pressures of 15-25 MN/m^2 (150-250 kg/cm^2) and lubricated with machine oil was extremely low. The wear-resistance of dies depends on the composition of the compound used in their manufacture: increasing the amount of iron powder reduces wear.

In the experimental and small-series production of thermoplastic test specimens and small batches of special parts by casting from master models, the use of metal moulds is not justified because of the great expense and labour involved. In these circumstances, it is economically advantageous to make temporary moulds from thermosetting plastics, especially when making parts of complicated shapes [8].

Figure 15

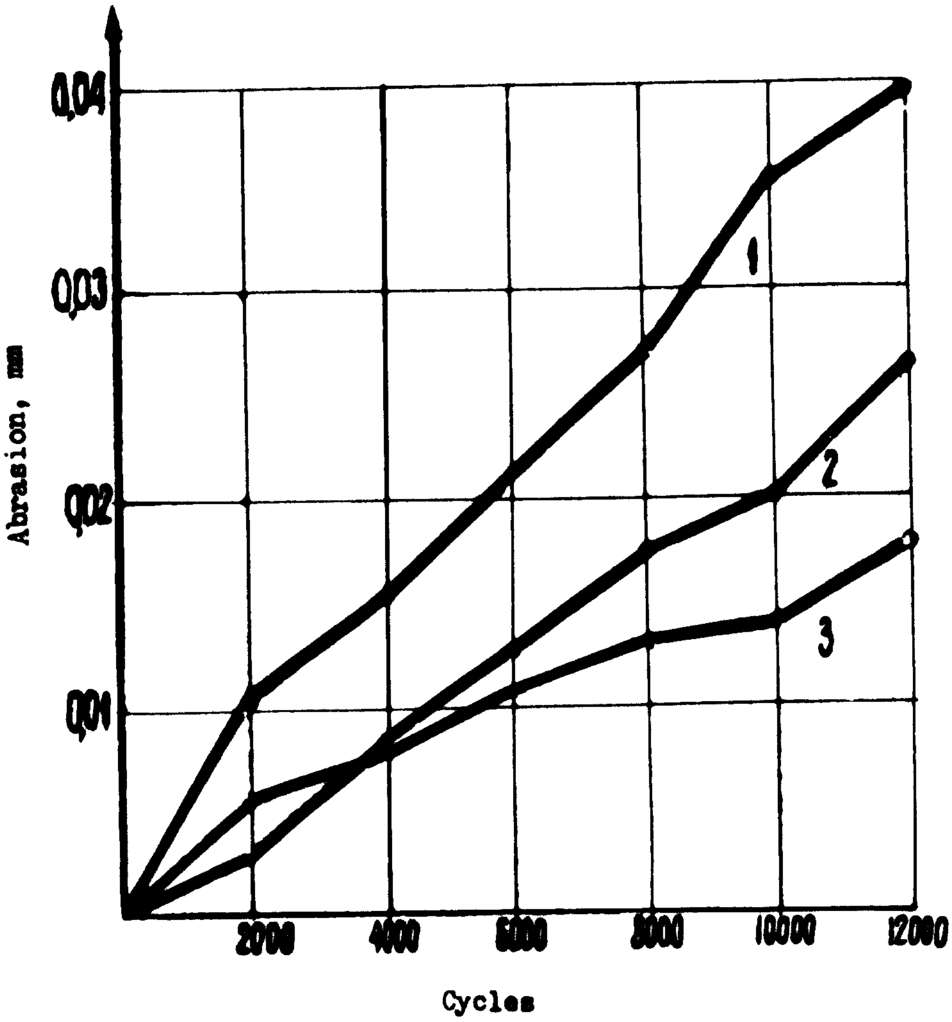
Kinematic diagram of an apparatus for the determination of the wear of plastic dies, and cyclogram of its operation



1 - Electric motor; 2 - Clutch; 3 - Reduction gearing; 4 - Shaft; 5 - Cam with special profile; 6 - Push rod; 7 - Calibrated spring; 8 - Tappet; 9 - Slides; 10 - Bevel gear; 11 - Eccentric; 12 - Test specimen in clamp.

Figure 16

Relationship between wear of epoxy compounds and number of loading cycles (load 15 MN/m^2 (150 kg/cm^2))

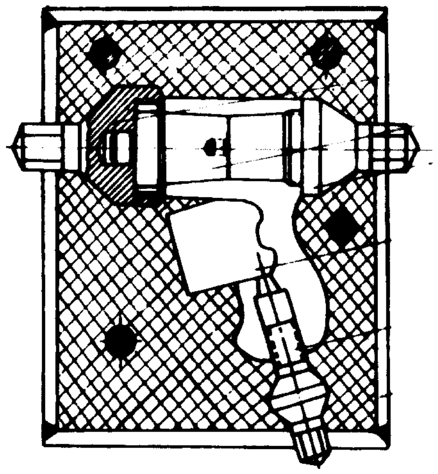


1 - 150 parts by weight of iron powder filler; 2 - 200 parts by weight of iron powder filler; 3 - 300 parts by weight of iron powder filler.

An example of a plastic casting mould is shown in Figure 17, which represents a mould for the casting in Capron of the body and handle of a power wrench. This casting mould consists of upper and lower half moulds contained in welded metal frames. The entire outer surface of the body of the power wrench, except for the screw threads, is shaped by the inner surface of the plastic half moulds, while the inner surface of the part is shaped by means of a number of mould inserts and cores, which also form the screw threads in the part.

Figure 17

Casting mould made of plastics for moulding the body and handle of a power wrench



1 - Lower half mould; 2 - Upper half mould; 3 - Pouring bush; 4,5,6,7,8 - Metal moulding cores; 9 - Welded frame.

The factor most influencing the dimensional accuracy of the cast part is the variation of the shrinkage of the thermoplastic material used to make the casting. Other factors, such as inaccuracies due to failure to mate the two halves of the mould tight against each other, inaccuracies in the preparation of the moulding elements, wear of these moulding elements, and fluctuations in the dimension of moulding elements because of temperature [illegible] etc."

[illegible] mould, etc., are [illegible] importance, and [illegible] calculating [illegible] elements [illegible] some of these factors are [illegible].

[illegible] elements in the mould must be so shaped [illegible] easy removal of the moulded part, so in determining the [illegible] dimensions it is essential to calculate the largest and [illegible] dimensions of the shaping elements.

[illegible] effective dimensions of male elements (Figure 18a) are calculated [illegible] the following formulae:

$$d_{\min} = d + a_{\max} + \delta_m \qquad (18)$$

$$d_{\max} = d + a_{\min} + \Delta_m \qquad (19)$$

For female elements (Figure 18b) the formulae are:

$$D_{\max} = D + a_{\min} - \delta_m \qquad (20)$$

$$D_{\min} = D + a_{\max} - \Delta_m \qquad (21)$$

where: $d_{\min}$, $d_{\max}$ are the minimum and maximum dimensions of a mould core, in mm;

$D_{\max}$, $D_{\min}$ are the maximum and minimum dimensions of a mould pocket, in mm;

d is the nominal design diameter of the cavity to be formed, in mm;

D is the nominal design diameter of the outer surface of the part which is to be moulded, in mm;

$a_{\max} = \frac{d S_{\max}}{100}$ and $a_{\min} = \frac{d S_{\min}}{100}$ are the greatest and smallest estimated values of shrinkage, in mm;

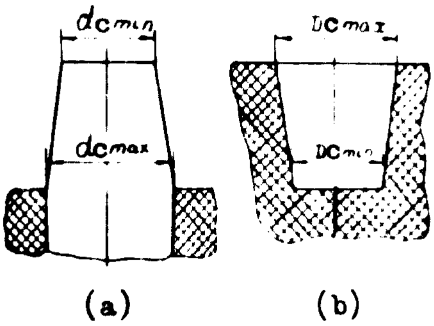
$S_{\max}$ and $S_{\min}$ are the greatest and smallest values of the shrinkage of the plastic, per cent;

δ_m is the manufacturing tolerance for the moulding element, in mm; and

Δ_m is the manufacturing tolerance for the moulded part, in mm.

Figure 13

Diagram for calculation of the effective manufacturing dimensions of moulding elements



a - Male elements; b - Female elements.

The effective dimensions of the male and female elements are subject to the following tolerances:

$$d_{c\,min}^{-\delta_m};\quad d_{c\,max}^{-\delta_m};\quad D_{c\,max}^{+\delta_m},\quad D_{c\,min}^{+\delta_m}.$$

If the moulding element consists of the plastic surface of the mould itself then δ_m is determined as follows:

$$\delta_m = \delta_f + \left(\frac{D\varepsilon_{\phi max}}{100} - \frac{D\varepsilon_{\phi min}}{100}\right) \qquad ([illegible])$$

where: δ_f is the tolerance in preparation of the original pattern, in mm, and

$\varepsilon_{\phi max}$ and $\varepsilon_{\phi min}$ are the greatest and smallest shrinkages of the plastic of which the mould is made, per cent.

When the tolerance zone is symmetrically located, the greatest and smallest dimensions must be determined and substituted in the formula for the calculation of the effective dimensions of the moulding elements. The value of the manufacturing tolerance Δ_m is excluded from the formula. Formulae (18) - (21) thus have the form:

$$d_{c\,min} = d_{min} + a_{max} + \delta_m \tag{23}$$

$$d_{c\,max} = d_{max} + a_{min} \tag{24}$$

$$D_{c\,max} = D_{max} + a_{min} - \delta_m \tag{25}$$

$$D_{c\,min} = D_{min} + a_{max} \tag{26}$$

where:

d_{min} and D_{min}	are the minimum design dimensions of the part to be moulded, in mm; and
d_{max} and D_{max}	are the maximum design dimensions of the part to be moulded, in mm.

The tolerances for the effective dimensions determined according to formulae (23) - (26) are determined in the same way as the dimensions determined according to equations (18) - (21). If the dimensions of the part to be produced are subject to close tolerances, the inclination of the shaping elements must be within the range 0.01-0.03 mm. In such cases it will be necessary to provide reliable means of ejection of the part from the mould.

In designing casting moulds it is essential to bear in mind that the inclusion of a metal framework in the cast part considerably reduces shrinkage of the plastic.

The process of making a temporary casting mould out of plastic comprises the following stages: preparation of the master model, the mould cores and the mould casing; preparation of the plaster foundation; preparation of the first half mould; preparation of the second half mould, and assembly of the two halves.

Metal, plastic or wooden models of the part to be cast can be used as the master model for the preparation of the casting mould. The surface smoothness of the original model must be of a very high order, and must be higher than the surface smoothness required of the part which is to be cast. It is therefore recommended that metal parts should be chromium plated and buffed, while wooden models must be polished and lacquered.

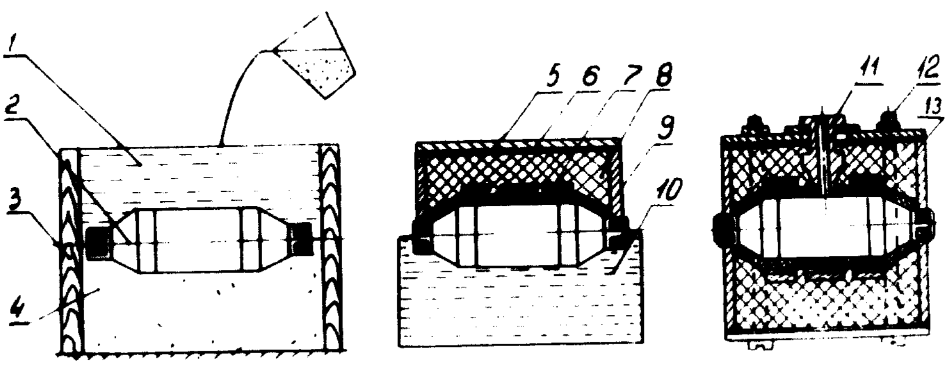
The mould cores are usually made of metal, and are normally solid in order to conduct heat away more effectively from the part being cast. The dimensions of the mould cores and collars must be worked out in the light of the shrinkage of the plastic. The surface smoothness requirements are the same as for the original models.

The cores are set in appropriate sockets in the original pattern, and must be reliably fixed there during manufacture of the mould. When preparing the plaster foundation, the original pattern, with the cores fixed in it, is moulded in moulding sand up to the breakline (Figure 19a) in a wooden casting box. The surfaces of the pattern and the walls of the wooden casting box must be covered with a separating agent consisting of a solution of grease in four parts by weight of kerosene. Epoxy compound must be cast only on a dry foundation, as moulds cast on a wet foundation are of inferior surface quality. The pattern, together with the cores, is installed on the dry plaster foundation, the surface of which is then covered with a layer of separating agent such as shellac, cellulose lacquer, or waterglass. These separating agents fill up the pores in the plaster. The surfaces of the pattern, the cores and the plaster foundation are then covered with a layer of separating agent, so that the compound will not stick to them. Separating agents which can be recommended for this purpose are a solution of grease in four parts by weight of kerosene or a solution of raw rubber in four parts of toluol, with the addition of glycerine. The separating coating must be thin and even.

When the plaster foundation has been prepared in this way, the metal mould casing is fitted on it (Figure 19b). In order to ensure the highest degree of adhesion of the epoxy compound to the walls of the casing, the inside of the latter must be cleaned of rust by sandblasting or with abrasive cloth and de-greased with acetone, alcohol or some other solvent. The ejectors are then installed, if necessary, and the compound, which consists of liquid epoxy resin, hardener, plasticizer and filler, is cast.

Figure 19

Process of manufacturing a casting mould from plastics



(a) (b) (c)

a - Preparation of the plaster foundation; b - Preparation of the first half mould; c - Preparation of the second half mould. 1,10 - Plaster foundation; 2 - Master pattern; 3 - Wooden frame; 4 - Moulding sand; 5 - Lid of frame; 6 - Layer of adhesive; 7 - Bronze inserts; 8,13 - Plastic flask for sand casting mould; 9 - Lining layer of plastic flask; 11 - Pouring bush; 12 - Bolt.

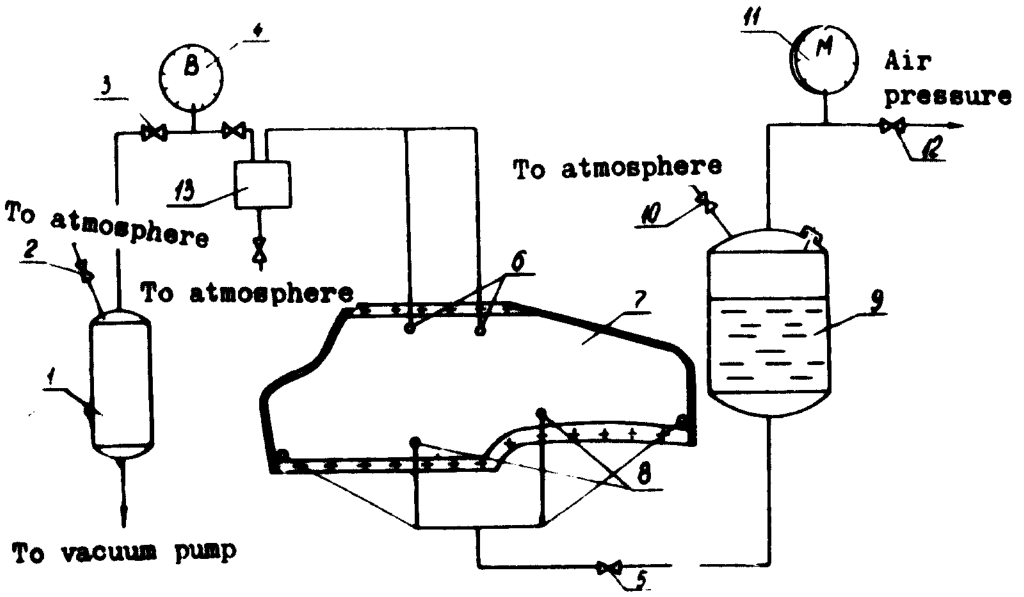
Plastic moulds for the production of wax models can compete with metal moulds, but moulds for the pressure casting of articles from thermoplastics do not have a very long service life (10-300 articles, depending on the pressure and temperature).

For the production of articles from glass fibre plastics by the method of injecting the binder into the mould (Figure 20), the mould can be made from glass fibre plastic by the contact moulding method.

The process of preparing dies for a motor scooter fairing is shown in Figure 21. The metal master pattern for the fairing is placed on trestles (Figure 21a) and a line of plasticine is placed all around its edge in order

Figure 20

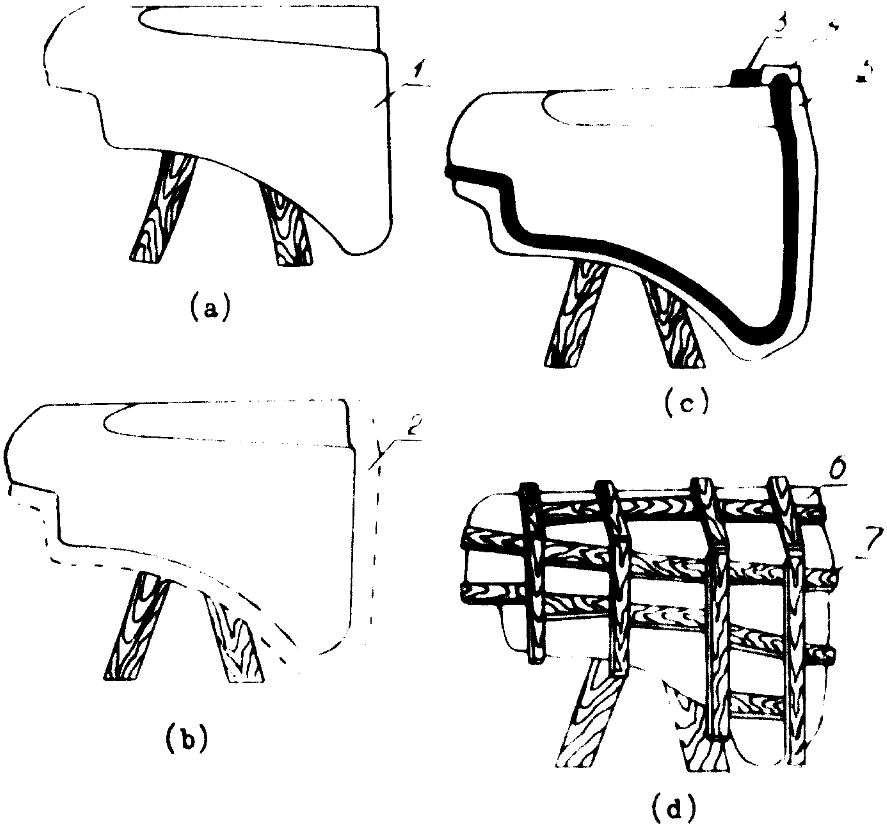
Diagram of equipment for the manufacture of motor scooter body sections by injection of the binder into the mould



1 - Reservoir; 2 - Tap for regulating the amount of vacuum in the mould; 3 and 5 - Taps; 4 - Vacuum gauge; 6 and 8 - Connecting pipes; 7 - Mould; 9 - Tank containing binder; 10 - Tap for regulating the pressure in the tank; 11 - Pressure gauge; 12 - Air valve; 13 - Trap and settling tank.

Figure 21

Method of manufacturing a press die from glass-fibre plastic



1 - Metal pattern; 2 - Plasticine edging; 3 - Guide batten; 4 - Template; 5 - Plasticine shoulder; 6 - Die matrix; 7 - Wooden strengthening members.

to create a shoulder (Figure 21b). This shoulder is formed with the aid of a special template (Figure 21c). The cleaned and degreased surface of the metal master pattern is then covered with a coating of separating agent so as to facilitate removal of the finished product. This prepared surface is then covered with a layer of polyester resin containing a thixotropic additive so as to prevent running of the resin down the vertical walls. After this layer of resin has been allowed to set for a little while, a second layer of binder is applied and covered with dry glass fibre material (glass fibre fabric) which is then carefully soaked with binder. In order to give the die high rigidity, wooden battens are moulded into the glass fibre fabric (Figure 21d).

Before the application of subsequent layers of glass fibre fabric, the processes of applying binder and soaking the fabric with binder are repeated. After being allowed to set for 18-22 hours at 18-20°C, the binder hardens and the article is removed from the mould.

The die thus prepared was then used for the moulding, in a similar manner, of the punch.

In order to make 2.5 mm high shoulders on the fairing, a 2.5 mm thick layer of plasticine was applied between the die and the punch during soaking of the glass fibre fabric. The fairing details which could not be produced in this way (such as apertures and holes) were produced by cementing cardboard cores on the master pattern. The working surfaces of the punch and die were then given a filling coat of epoxy plastic and polished, and pipes for introducing binder and releasing air from the mould were cemented on the die. Proper sealing of the mould when assembled was ensured by a rubber gasket cemented to fit the shape of the die. For series production conditions, the amount of time and money needed to make such punches and dies is 3-10 times less than that required to make comparable metal units.

The above-mentioned advantages and the wide field of utilization of plastics in the manufacture of production equipment make possible the extensive employment of plastics in machinery manufacturing, particularly in small-series production. Plastics must only be used in production equipment, however, if: (1) their reliability in operating conditions can be assured and (2) their use reduces the amount of time and money spent on the preparation of production equipment, compared with equipment made of more conventional materials.

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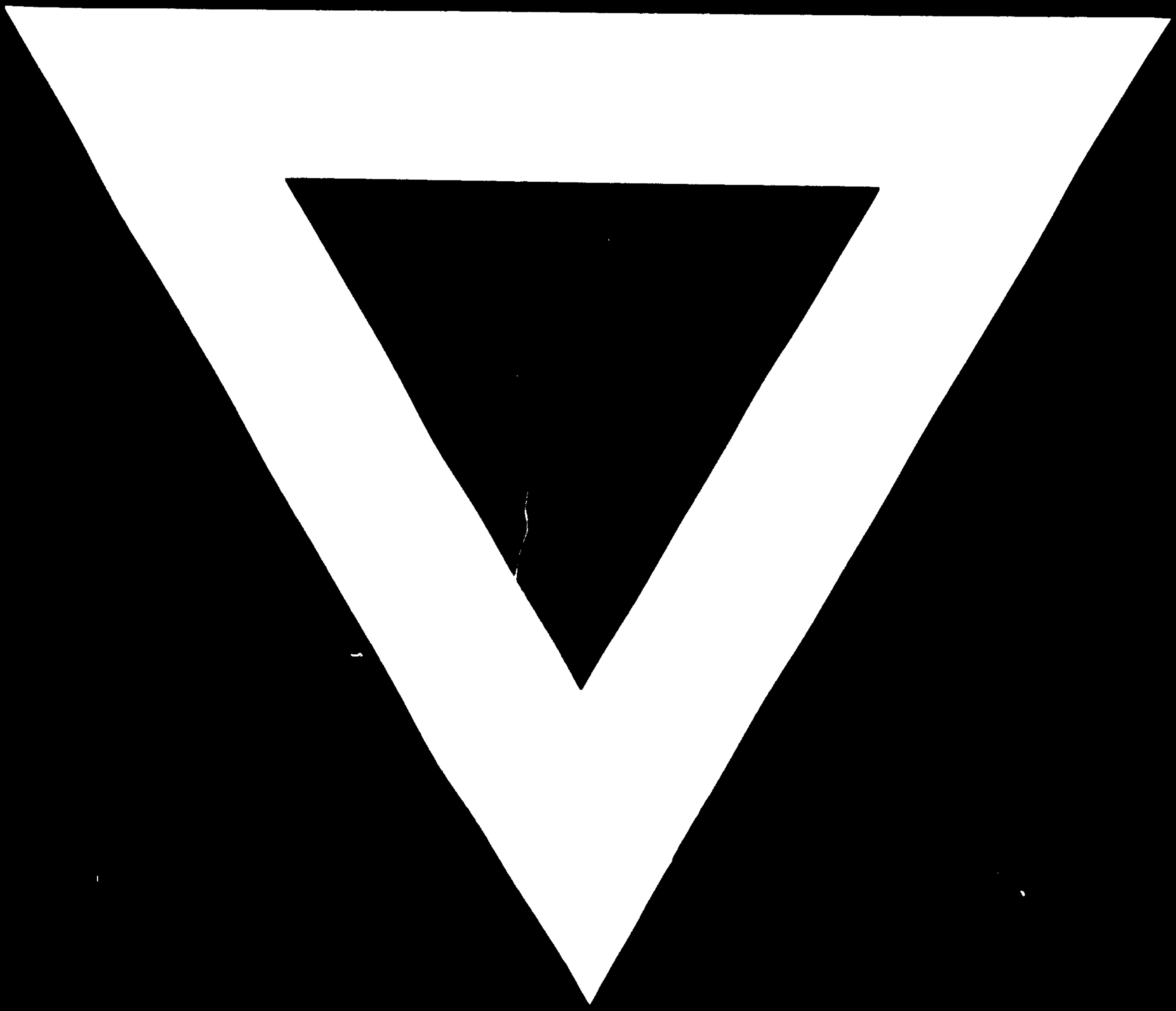

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