COMMENTS ON RESULTS

(1) Influence of Gas Pressure

Among the possible causes of the yielding of a mould expansion to thermal shock not only the expansion of the sand but also the gas pressure could be considered to be of great importance. There are a number of facts which prove that the expansion is the main cause. The great difference between moulds made from quartz sand and other, less expanding sands, the occurrence of a sand rain and the character of the spalling can be mentioned as examples. An opinion, which was earlier generally accepted, however, was that scabs and related defects were caused by the pressure of the gases evolved in the mould when it was rapidly heated by the poured metal. Also now many foundrymen believe that gas pressure is the real cause of scabs or that it at least contributes highly to their formation. The results of this investigation, and also of all others where the factors have been controlled and the occurrences carefully observed, do not support this opinion. From the present investigation the following examples can be elicited. If the quartz sand is exchanged by some other material the spalling resistance is very considerably increased. In a series of tests with sands with an average grain size of 0.3 mm, where only the type of sand and the grain size distribution were varied, the permeability values varied from 20 to 240. In general, the most stable moulds were those with the lowest permeability values and the moulds most liable to spalling were those with the highest values. Moulds dried through storage were more resistant than fresh moulds with a much higher moisture content. The relation between spalling resistance and moisture content (Fig. 6) shows that if the moisture content is increased above the normal values an increase in spalling resistance rather than a decrease is obtained. The moulds which developed the greatest quantity of gases, i.e., those containing cereals or coal dust, were also those most resistant to spalling.

It can be shown by calculation that if the water is vaporized from a 0.5-mm thick layer containing 10 per cent moisture in a second and if all of it passes through a 5-mm thick surface layer of a mould with permeability number of 30 the pressures exerted by the gas is only about 0.15 g per sq. mm. Still this case is much more drastic than normal conditions. If the surface be very dense, the pressure can no doubt be higher, but it is evident that gas pressure in normal cases must have very little influence on the spalling of a mould.

It may be argued that gas will be a much more important factor when scabs are formed at the bottom of a mould cavity when hot metal flows over the mould surface. However the pressure of the gas on the dried and heated surface layer can still not be high in the first few seconds as this layer is then very thin and later when it is thicker the static pressure of the metal will probably be higher than the gas pressure and a solid metal skin also forms which will help to inhibit the spalling. Besides if scabs were formed in such a manner that gas pressure pushed from a layer of molten sand into the metal, then some of the gas must bubble into the metal. In fact a much less general boiling should occur. It is only exceptionally that buckles and scabs are connected with such porosities as would then result.

It is moreover the Author's opinion that the formations of "bottom" buckles or scabs is never started under a layer of molten metal. Observations during casting experiments indicate that the process is the following: The molten metal flows into the mould in one or more streams. Under these streams the adjacent sand expands rapidly and if the pressure is great enough the layer will move outwards, a crack may form and a piece of the layer may be partly or completely detached from the mould by shearing. The cracks will form where the sand is weakest, i.e., where it is not covered by metal. The pressure of the metal also helps to keep the sand down. After the crack has been formed the further development of a buckle or scab can proceed under molten metal.

(2) Influence of the Thermal Expansion of the Sand

The intimate relation between the failure of the mould wall and the thermal expansion of the sand is well established by the results of the present investigation and earlier by the work sponsored by the American Foundrymen's Society and by investigations made by the staff of the British Cast Iron Research Association. One of the AFS committees has reported a good correlation between the formation of rat-tails and the relation between the hot compressive strength at 540 or 595 deg. C. and the maximum confined expansion of the sand measured in a quartz tube by shock heating at 815 or 1,480 deg. C. A combination of a low hot-compressive strength and a small expansion is said to give the best results. Another committee has reported a good correlation between the tendency of scab formation and the temperature at which the curve representing maximum strain, i.e., temperature for the sand crosses and rises above the curve.
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representing the confined expansion, i.e., temperature for the sand. The lower the temperature is at which the curves coincide, the less the probability of scab formation is said to be. The opinion advocated by the staff of the BCIRA is that the character of the stress-strain relation of the sand in compression is practically all-important, although of course it is considered against the expansion curve (free expansion) which does not vary much so long as quartz is the chief ingredient.

A slow decrease of the stress after the maximum stress is attained is considered to be the distinctive feature of a sand with which the tendency of scab formation is small. An ingenious equipment has been constructed for the examination of the stress-strain relation under compression at arbitrary temperature. The confined expansion test used in the U.S.A. as a measure of the expansion tendency of the sand represents a complex of fundamental properties and is apparently not very well understood. On the other hand the test conditions simulate to a certain degree the conditions in a shock-heated mold. It is not perceivable, however, why there should be a relation between this expansion and the hot compressive-strength, such that the increasing effect of increasing expansion on the tendency of scab formation can be computed by a proportionately decreasing hot compressive-strength. It is much easier to understand why there should be a relation between the ultimate strain by compression and the thermal history of the sand. However, the temperature at which the strain curve crosses the expansion curve is reported to have been 830 deg. C. or higher. At these temperatures the sand has already ceased to expand. One would rather believe that the maximum stress at temperatures below 575 deg. C. would be decisive. It is interesting to learn that nevertheless, considerable agreement has been obtained with the results of testing experiments, when sands bonded with fire clay or varying percentages of bentonite were used. The British investigations have not yet advanced so far that it is possible to say how well their hypothesis agrees with actual performance. Anyhow it seems not to be possible to explain from the reported results the difference in spalling behaviour between sands bonded with a kaolinitic clay and sands bonded with bentonite.

The background of the suggested relations between certain physical properties of the moulding sand and its behaviour in a mould with respect to the formation of scabs and related casting defects, is, of course, the fact that normal sand-testing gives no information about this behaviour, which is a very serious limitation. The Author's opinion is that foundrymen have not learned much more about what happens in the moulds when they are exposed to thermal shocks of different types from the mould metal, before any reliable laboratory tests can be recommended. It is obvious that some high temperature test is necessary and so the fundamental work done in this field, and as yet this has almost exclusively been done in the U.S.A., is very valuable.

What the Author feels as a void in the treatment of the problem so far, is that too little consideration has been devoted to the consequences of the steep temperature gradient prevailing in the mould during pouring. One consequence is that a comparison between the expansion and the capacity of deformation should be made over a range of temperatures and the net effect calculated by integration. Even then the results could be very misleading as in practice a levelling of the theoretical stress distribution will occur. Probably as a result of this dilemma there is no mention of, or an uncertainty in, the American and English literature about what temperature should be chosen for the comparison. Another important consequence of the temperature gradient is that rupture does not occur in the same manner in a mould wall suddenly heated from one side as in a uniformly heated test piece. In fact there are two kinds of rupture which must be considered in the shock-heated mould, namely the one approximately parallel to the mould surface and the one that takes place at an angle to the mould surface. The latter is the one most closely connected with the rupture occurring in compression tests. The former, which seems to take place at the interface between the dried layer next to the surface and the wet sand behind, is completely neglected in the above named hypotheses. No distinction is made there between the behaviour of dry and green moulds. In a paper where the casting defects caused by the thermal instability of the moulds are discussed, Nicolas suggests that the spalling of green sand mould occurs at the interface between dry and moist sand. No further reference to this important aspect on the problem has been found in the literature.

(3) Aspects of the Process of Spalling

In what follows, the Author will try to outline his conception of how a green sand mould fails and why it fails when it is exposed to the sudden indirect heat from molten metal. The views are based on the observations made during this investigation and the picture given this applies at first hand to the type of mould and of heating that has normally been used during the investigation. The sand material is supposed to be quartz.

During the first moments of heating only a layer of one or two sand grains' thickness will be affected. The expansion of these sand grains meets little resistance in the direction towards the mould cavity but a great resistance in the other directions. On many sand grains the lateral stresses will impose a resultant stress in the direction out from the mould, and if this stress resultant is greater than the bonding strength, the grains will be squeezed out from the mould—a sand rain will occur. Due to the release of sand grains, and also to the rearrangement of other sand grains, the lateral stresses are kept within moderate limits. The sand rain will reach its maximum as the surface grains are transformed to the high-temperature modification of quartz.

As the heat penetrates deeper into the mould the distance between the isotherms representing beginning and end of expansion decreases at first. Thus an expanding layer of decreasing thickness moves...
inwards followed by a growing layer of practically volume stable sand. At the same time, moisture accumulates in front of the expanding layer in the neighborhood of the 100 deg. C.-iso-therm. (In order not to complicate the picture unnecessarily the lower temperature limit of the expanding layer is put at 100 deg. C. Up to this temperature and even a little further the expansion is also negligible.) As long as the expanding layer has not the thickness of a few sand grains it is not mechanically very stable, the grains are relatively easily rearranged and the lateral stresses can not become very high. As the expanding layer increases in thickness its strength also increases.

At the same time, the exterior hotter layer also becomes stronger and counteracts the movement of sand grains towards the surface. Thus the lateral stresses in the expanding layer will increase. An important consequence of these changes is that instead of the nearly individual movements of the sand grains in the early stage, there will now be a movement of more coherent layers in the directions where the resistance is smallest. The increase in thickness of the expanding layer, which will follow later, is accompanied by a decrease in the rate of heating. Thus there will be more and more time for the moulding sand to undergo plastic deformation. This will tend to diminish the stresses. Further, as the thickness of the expanding layer increases the gradient of the lateral stresses decreases and at the same time the shear stresses also decrease. The increased thickness and strength of the exterior hot layer may have the effect of reducing the strain of the expanding layer to some extent. In any case the transverse strength of these combined layers is increased. It is then quite natural that there is a critical time of heat exposure. If that time is attained without yielding, it is quite probable that there will be no spalling at all.

The loosening of sand grains at the exposed surface is the first sign of failure. What will happen later is determined by several factors, the most important of which seem to be:

(a) Magnitude of the shear stresses at the interface between dry and moist sand.
(b) Relation between shear stresses and strain at this interface.
(c) Relation between strain and cohesion at this interface.
(d) Magnitude of the tensile stresses (caused by the gravity and other factors) which tend to pull the surface layer from the moist part of the sand.
(e) Magnitude and distribution (especially in the directions parallel to the mould surface) of the lateral compression stresses brought about by the heat expansion of the sand.
(f) Relation between tension and compression stress in the expanding layer at different temperatures. Especially it is of interest to know the maximum stress before a pronounced breaking occurs or before the stress decreases much below the maximum stress.

(c) The relation between stress and strain in the exterior layer where the expansion of the sand has already ceased.

(d) The heat conductivity of the mould.

Para (a) is intimately related with (c) and also with (d). There is a great complexity of properties which it is difficult to survey. The most important properties of a green mould with high spalling resistance probably are: (a) That it has a high heat strength and (b) that the layer where the sand grains are expanding can stand a great deformation before it breaks.

It is in fact very dangerous to speak of the formation of the transverse cracks and the parallel ruptures of a layer in separate processes. They are intimately interwoven and exert a mutual influence on each other. It is true that it is possible to imagine a separate transverse rupture, a partial disconnection and outward bulging of a layer without an observed crack, and such a performance has been observed. It is, however, not common and must therefore be a transverse break which is accompanied by a crack at the interface between the dried surface layer and the moist sand behind, and that the layer where the sand grains are expanding can stand a great deformation before it breaks.

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Anyhow the loosening of a layer facilitates the formation of transverse cracks—the difference in spalling resistance between dry and green moulds is explained by the ease with which a layer slips and is disconnected in a green mould. The transverse breaks, cannot develop to any high degree until the layer has begun to slip. On the other hand, this sideways movement is immediately and most considerably increased as soon as a crack has formed and during the slip the layer is released from the mould. Because of the shear stresses the transverse breaks will aid to pull the layer away from the rest of the mould. If these facts are kept in mind it may be permissible to consider the two types of failure separately as, in the Author's opinion, the process is then better understood.

The sideways movement explains the influence of the size of the heated mould surface. If there were no such movement the stresses and strains would be independent of the size of the mould. In practice an adjacent heated surface layer can expand to some extent towards a less heated or weaker part. The distance of expansion before a break occurs is determined by the stress-strain relation in the yielding part. When the ultimate stress is attained there, a local compression or shear follows by a rupture will occur in a narrow zone. The extension of the expanding layer during the process of rupture is thus approximately independent of the size of the mould. The relative lateral expansion of the heated layer, however, is inversely proportional to the linear size of the heated surface. The relative linear expansion corresponds to an equivalent decrease of the confinement of the expansion (i.e., the compression) and thus a decrease of the stresses in the expanding layer. At a given time of heating the compressive strain should be the smaller, the smaller the heated surface is—all other conditions being the same. Another somewhat oversimplified
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way of expressing the same thing is the following—a certain distance of sideward movement is necessary before a rupture occurs. The relative expansion necessary for this extension of a layer is greater the smaller the layer. It is then natural that there is a critical size of the heated mold surface (when the other mold properties and the heating conditions are given) such that a mold of this or a smaller size cannot stand the heat effect practically any time without spalling. The experiments indicate that the spalling resistance decreases rapidly at first and then successively slower as the size of the mold is increased above this critical size. This is what could be expected according to the above considerations although it is not likely that they give the whole story.

Taking into consideration the complicated combination of stresses and strains in the heated surface layer and the non-compact layer, it is not surprising that the spalling process occurs in several ways. If the dried surface layer breaks in a brittle manner already at a very small strain (approximately the extension) layers of very small size are peeled off, and the spalling resistance is small. As the brittleness of the surface layer decreases, the peeled pieces become larger. As a rule the spalling resistance increases at the same time. However, even if the whole heated surface layer is peeled off as a unit, the spalling resistance can be medium. In such cases the cohesion between the dried surface layer and the wet sand beneath is obviously bad. In some molds which have been so resistant that no spalling has occurred, it has been observed that a fairly thick layer (about 0.5 in.) has been sintered and separated from the rest of the mold. The cohesion, however, was still very good. In this case the compressive strength of the expanding layer must have been high and the disposition to crack formation small.

The "snow-flake" type of spalling that may occur, especially when the sand is very fine grained and the moisture content low or moderate, resembles to a certain degree the spalling that was often obtained with ball clay as the only binder. In both cases the released pieces were small. The differences are that in the "snow-flake" process the flakes have an irregular thickness, they often have approximately the shape of a cone-cone lens, and that the "snow-flake" process is much slower than the other process. The thickness at the center of the flakes indicates that they were formed by a shear process started at the level where the quartz was being transformed. The principal reason for this must be that in the mold where the small irregular flakes are formed, the transition region between dried and unried sand is not particularly weak. A shrinkage action at the mold surface, caused by the sintering of the surface grains, also seems to help to form the flakes, that the sand is generally very fine grained, when this type of spalling occurs, it sinter comparatively easily and this tendency may be added to by the relatively high surface-temperature that is to be expected with such sands.

Another type of yield is the one obtained, when the molds are very weak, e.g., owing to very coarse-grained sand with a narrow grain distribution. This type which is here called sand-fall is characterized by the sudden falling of a great part of the exposed half-mold. The explanation ought to be that owing to the weakness of the mold the relatively small shear stresses that arise at the depth where the rupture occurs are sufficient, when they are added to the tensile stresses existing there because of the gravity, to bring about the rupture.

(4) Rate of Heating

It is natural that a slowly heated mold resists the heat effect better than a more rapidly heated mold as the temperature gradient, and likewise the stress gradients, will be small in the slowly heated mold. As the rate of temperature is slow, the sand grains will also have more time to occupy stress releasing positions and there will be more time for the interstitial material to be plastically deformed and both these circumstances tend to decrease the stresses.

It is not so obvious why the resistance increases with increasing rate of heating above a certain high rate. There are, however, acceptable explanations. If the rate of heating is very high, the expanding layer, larger than usual, will be very thin and therefore a relatively great part of the expansion work will be a transverse (outward) movement of sand grains and thus the lateral stresses will not be very high. Of course the thickness of the expanding layer will gradually increase and then also the lateral stresses. The exterior layer, where the sand has already ceased to expand is thicker, however, when the heating rate is high, than when it is low when the thickness of the expanding layer is the same and, therefore, when the stresses would normally be high enough to produce rupture, the thickness of the two attached layers may be great enough to resist the stresses from the expanding layer without rupture. From the results of the experiments it is also clear that a slight sintering can improve the strength properties of the ultimate surface layer. That is another, and perhaps the most important, reason why the resistance can increase with increasing heating rate. The effect of sintering has been established not only by the direct results with quartz sands of different sintering points, but also by the indirect results with a quartz sand that sintered at low temperatures, which was tested with and without the admixture of a coal-dust with low gas content. The coal-dust decreased the sintering tendency of the sand and also decreased the spalling resistance of the mold.

Another circumstance, that should be considered in this context, is that, particularly with cast iron, the heat emission may be lower at some high temperature, when there is no slag film, than at a lower temperature when there is a slag film. The shape of curve (b) in Fig. 4 is probably explained by the difference in heat emissivity.
(5) Sand Material, Grain Size and Grain Distribution

The results with various materials other than quartz are consistent with the expansion curves, which is unusually unfavourable for quartz. The most important reason why the spilling resistance increases with increasing grain size probably is that the temperature gradient becomes smaller when the grain size increases, a consequence of the increasing thermal conductivity. It would also be possible that the heat shock is reduced when the sand grains are big, as the rise of temperature must be slower at the centre of the grains than at the surface. An approximate calculation shows, however, that a grain of 2 mm diameter, the surface of which is suddenly heated to 600 deg C, will have a centre temperature of 550 deg C after 0.4 sec. This delay is not very great and although the lag decreases very rapidly with decreasing grain size it seems probable that the effect of the temperature lag in the grains is small. As the temperature gradient is steep there must, however, be a considerable difference in temperature between the grain surface that is next to the mould surface and the opposite surface when the grains are big. It is not easy to foresee, however, the consequences that this fact may have on the stresses in the mould.

Another difference between fine and coarse sands lies in the distribution of the binders and admixtures. Over a given distance the integrated thickness of the individual layers is at least approximately the same in all cases if the percentage of the interstitial materials is the same. However as the grain surfaces are irregular and the individual layers thinner when the grain size is small, it is possible that the distance available for plastic deformation will be smaller when the sand grains are fine. The increasing grain pressure, that is combined with decreasing grain size, may have a small but in no way decisive effect.

The fact that the spilling resistance increases with increasing widthness of the grain size distribution may have several causes. The heat conductivity is increased and thereby the temperature gradient is reduced; the grains at the same average distance from the mould surface do not expand simultaneously and the mobility of the grains may be increased when many grain sizes are mixed. The increased mobility of the sand grains, and also other factors, increase the maximum strain. The strength is also increased but this is probably valuable only in connection with the transition zone between dried and moist sand. If the strength in this zone is increased, the spilling resistance should be increased. It is in fact to be expected that the resistance against slip in this zone should be greater when the sand grains have a wide size distribution than if they are all of the same size. The influence of the sintering tendency of the grain material has already been mentioned. A low sintering temperature may evidently be favourable. This effect, however, is more or less completely suppressed by the addition of organic compounds.

(6) Quality and Quantity of Binder

If the properties of clays that have given good results are compared with those of clays that have given poor results, it is found that the best clays give much higher dry and hot strength and have a much greater swelling capacity (gelling index) than the poor clays. If natural sodium bentonite is compared with ball clay as typical examples of good and bad clays, the following conclusions can be made. In moulds bonded with Na-bentonite the spalled layers are big, while in moulds bonded with ball clay the surface layer is cracked in small pieces in a brittle manner. This gives the case that the content of ball clay is so much greater than the bentonite content that the dry or hot strength is about the same in the two types of moulds. This indicates that the important difference is that the bentonite makes the mould more elastic-plastic than the ball clay. It is also to be expected that the great swelling capacity of the sodium bentonite should give the mould a relatively high maximum strain by compression as the interferences between the sand grains should be filled with a relatively low percentage of solid bond. It is remarkable that there is no real support of this supposition in the literature. The results of the experiments with separate layers of different clays also indicate that the strength properties of the region where dried sand is in contact with the mould surface become better when the bond is bentonite than when it is ball clay.

That an increasing clay content in the mould increases its spilling resistance is probably explained by the thereby increased capacity of the sand of being compressed without bursting—greater maximum strain. It is however of a certain interest that the simultaneously increased dry and hot strength of the expanding layer does not increase the tendency to spall as it is sometimes asserted in literature that a high strength is dangerous. This remark also applies to the difference between sodium bentonite and other clays.

(7) Moisture Content

The relation between the moisture content of the sand as mixed and the spilling resistance of the moulds, which was obtained by the experiments, is not so easy to explain. The surprisingly great resistance that was obtained with low moisture contents, especially with swelling bentonites, but also with ball clay, though at still lower moisture contents, seems to be connected with the very stiff consistency of the clay at those low moisture contents. The clay in contact with dried sand does not act so much as a bond as a material that yields when the sand expands. The cushioning effect would also explain the great difference in results with the highly swelling bentonites and ball clay. It is of interest in this connection that when the swelling capacity of the bentonite was destroyed by hydrochloric acid a relation between spilling resistance and moisture content similar to that with ball clay was obtained.

The fact that the spilling resistance decreases when the moisture content is increased to normal
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values is probably due to the then increased strength of the moulding sand which confines the mobility of the sand grains and causes the stresses to increase without an equivalent increase in maximum strain. That a further increase in moisture content does not decrease the spalling resistance, but rather increases it, might be explained by the somewhat denser packing of the sand that is obtained at high moisture contents, which may increase the shear strength at the interface between the drier and the moist sand.

(8) Additions of Coal-dust, Cereals and Sugar

The beneficial effect of coal dust in moulding sands is considered to be that the material is plastic, has a conditioning effect, particularly at the temperatures where the sand expands. The view in the Author's opinion holds in distinction. It is hardly pure incidence that such substances as pitch, cereals flour, dextrin and sugar have a similar effect as coal-dust. What all these substances have in common is that at the temperatures existing in the expanding layer they function at least for some time as viscous binders. They also all give off distillation products at high temperatures. The poor result with coal-dust with "low gas content" confirm that it is the distillation products, probably the tar and pitch, that are the valuable constituents in coal dust.

The results of the experiments with separate layers indicate that it is not only the properties of the expanding layer that become favourable by the addition of these organic substances but also the properties at the interface between dried and moist sand. These experiments also indicated that the substances in this group could have a favourable influence even if only distillation products arrived at the expanding layer.

(9) Other Additions

The addition of substances insoluble in water—1 or 2 per cent iron oxide or chalk powder, 5 per cent. dead-burnt bentonite, 6 per cent. lump black or up to 10 per cent. silica flour—to a mixture of sand, bentonite and water made but little difference. Sometimes the resistance was a little better, sometimes a little worse than without the additions. This is not very surprising, though the opinion is often heard that "dust," that does not act as a binder, has an unfavourable influence. In fact a negative influence could be expected, since the fine particles will decrease the amount of binder available to the sand grains. If the mixing operation is not satisfactory this effect can certainly be a serious disadvantage. With too much silica flour it is also possible that the expansion shock could be more powerful than in other moulds. On the other hand, if the particles are well distributed, and the percentage not too high, they should make the moulds more plastic. In American literature it is often seen that silica flour increases the tendency of formation of scabs and related casting defects, and that the reason should be that silica flour increases the hot strength of the sand. The explanation can hardly be true as no particular high-temperature effect of the silica flour exists at the relatively low temperatures in the expanding layer and an increase in strength in the hottest layer where the sand does no longer expand should rather be useful. Besides the whole conception that a high strength in itself should be detrimental has found no support in this investigation.

Water soluble substances with acid reaction, like hydrochloric acid, boric acid and oxalic acid definitely decreased the spalling resistance when added to sand mixtures bonded with sodium bentonite. This effect seems to be connected with the fact that the swelling capacity of the bentonite is strongly reduced if the pH of the liquid is lowered under a certain value.

Sulphite lye also decreased the spalling resistance of bentonite bonded moulds. In this case the relation between this effect and the swelling of the bentonite is not so obvious. Experiments showed that the two qualities of sulphite lye used in the mould, reduced the viscosity of an originally fairly stiff mixture of bentonite and water considerably, though only when the proportion between lye and bentonite was small, much smaller than in the moulds. When the proportion was higher the viscosity increased again and was soon higher than initially. The increase in viscosity may be caused by the swelling of the sulphite lye itself. In contrast to this behaviour, the spalling resistance decreased continuously with increasing lye content in the mould. It is evident that something "detrimental" happens to the bentonite. It is true that both qualities used showed acidic reaction in water solution, but even when neutralized with soda, the lye had no positive effect despite the sugar content. It is possible that the lye in itself reduces the plasticity of the moulds at high temperatures.

(10) Storing of Green- and Dry-sand Moulds

The experiments made with stored moulds in this investigation have shown a spalling resistance much superior to that of corresponding green moulds. Also moulds made from moulding sand of low moisture content have shown good resistance. It is then indeed surprising that moulds that have dried during storing so that the moisture content has decreased from the original 2.8 per cent. to about 0.5 per cent., have practically the same spalling resistance as fresh moulds. This result, however, is in good agreement with the circumstance that over-dried moulds which were stored until they picked up a moisture content of about 0.4 per cent. also behaved as undried moulds. It is clear that it does not matter very much what the moisture content is when the mould is used, with the exception of very low moisture content. The important thing is what the moisture content is when the mould is made. It is also this latter condition that decides the structure of the mould. The most important influence that a change of the moisture content after the mould has been made can have on the spalling resistance, is that it changes the differences in moisture content at the region where the surface
layer, that has been dried by the heat from the molten metal, is in contact with the still not dried moulding sand. From the results it is evident that it is not possible, by storing in normal atmosphere, to get down to such low moisture contents, that the strength properties of this region are considerably changed. Judging from the results with the standard moulds, there is a critical value of the moisture content not much below 0.4 per cent, that marks the difference between dry and green moulds. This does not mean, however, that there would be no difference if the moisture content were 0.5 per cent, but only that the spalling resistance seems to increase rapidly when the moisture content is lowered to or below the former value.

(11) Ramming Density (Mould Hardness)

The fact that a minimum of spalling resistance was obtained at a certain ramming intensity indicates that at least two factors are influenced by the ramming in such a way that the charges have the opposite effect on the resistance. When the ramming intensity is increased the sand grains are gradually packed closer. Thereby the chance of a grain to expand without forcing other grains out of their place (or be forced away itself) is decreased. Thereby also the resistance to spalling decreases. It would be natural if this detrimental effect of the denser packing would cause the spalling resistance to decrease continuously and even at a successively growing rate. The results of the experiments however was that after a range of mould hardness, within which the spalling resistance decreased rapidly with increased hardness, the decrease slowed and was even changed to a slow increase. The most likely explanation of this behaviour is that it is caused by the increased strength of the mould. Whether it is the increased rigidity of the expanding and the hotter layer or the increased resistance against slip in the transition region between dry and moist sand, that is decisive, can not be settled by the results of the experiments.

Another important question in connection with ramming is the effect of uneven ramming on the spalling resistance. Uneven mould hardness must provide a tendency of harder layers to move towards adjacent softer layers during the heat exposure. Such movements should limit the compression stresses in the hard regions and increase them in the weaker regions. The effect of the movements on the spalling resistance depends on several factors, some of which will be mentioned later.

If the stresses at completely confined expansion in the harder regions are not greater than the maximum compression stresses in the looser regions there should be no failure (Fig. 9). This case corresponds to very loose ramming. The more the stresses at completely confined expansion in the hard regions exceed the maximum stresses in the less hard regions, the greater the chance is that the weaker regions will break. As the maximum strain is normally greater in the less hard regions there, however, not be any break, and the chance of breaking should also be greater the larger the hard regions are in comparison with the less hard regions. If the hard regions is taken as a standard of comparison the relation of the sizes is however eliminated from the comparison. The argument is best illustrated by an example. In Fig. 9, the two curves represent the integrated stress-strain relation in two adjoining regions (in situ, not as free layers) one region being harder rammed than the other. For the sake of simplicity the areas of the regions are assumed to be equal. If a break occurs at a compressive strain that is less than the average OC' of the strains necessary to break the individual layers, it is assumed that the hardness difference makes the mould more inclined to spalling. If the acceleration stresses are left out of the discussion the stresses in the harder layer should not exceed the maximum stresses in the looser layer, i.e., they should be OD' = OB' and the strain = OD'. The average strain when the looser layer breaks = OD' + OB' = OD' + DB' which is smaller than OC' = OA' + AB' / 2. In this example the break thus would occur at a much smaller strain than it should have done if the ramming had been of a uniform and intermediate hardness. It is obvious that the result of this very schematic reasoning depends on the shape of the curves. The possible weak point, however, is not to be found in the shape of the curves as all pairs of natural curves give the same result.

Fig. 9.—Hypothetical stress/strain curves for (A) a hard-rammed and (B) a less-hard-rammed part of the mould; curve (C) is the average.

The harder a mould is rammed, the less the differences in hardness become. A moulding to the above, this change is also a possible explanation of why very hard ramming makes the moulds less inclined to spalling than somewhat looser rammed moulds, despite the decreased space for expansion of the sand grains. The very rapid increase of the spalling resistance that was obtained when the hardness was decreased under normal values was interrupted at a certain hardness limit when the moulds began to "collapse" instead of the normal more superficial
Spalling of Green-sand Moulds

Flaking. The cause of this collapse has already been discussed (Paragraph 3).

(12) Relation between Spalling Resistance and Test Values Obtained by Normal Sand Testing

The only ordinary sand test which has been found to have some relation with the spalling resistance is the bulk density of the dry moulding sand. This relation however is not constant. Sometimes a decaying bulk density corresponds to an increasing resistance. In general there is a relation of this kind when the hardness of the moulds is varied, though, of course, this comparison is outside the scope of ordinary sand testing. When the moisture content of a moulding sand was varied, the bulk density increased more at the same time as the spalling resistance. When moulding sands with different base sands but otherwise of similar composition are compared a clear tendency has been observed of an increased spalling resistance with increased bulk density. This is a relation between bulk density and spalling resistance is often direct and not inverse as one would expect. This may be a reflection of the increased flaw density that is often increased with an increased density, but may also indicate that a natural close packing makes the moulds mechanically more stable.

REFERENCES


DISCUSSION

[At the Congress, this Paper was presented by the Author in person.]

Mr. W. B. Parke, opening the discussion, said he was doubtful as to how far spalling was due to an increase in dry-strength, since no increase occurred.

With regard to test castings, he would not disagree with the Author at all, for two people working with totally different materials the results were surprisingly in agreement.

Mr. H. Haines said, as far as spalling was concerned, he had had great difficulties in this respect when green-sand moulding flywheels of 4 tons, and in one case one mould in green-sand a casting up to 20 cwt. with no spalling whatever. The technique of the foundry was governed by years of experience but the essence of testing was the feel of the sand, which he claimed could not be explained at conference or put on paper, because a skilled moulder could tell from the feel of his sand whether he was going to have spalling or not. The more moulders that could be encouraged to take an interest in the feel of the sand the better it would be. He had recently written a paper entitled "Is Green-sand Moulding Deteriorating?" which he hoped would be a challenge to all foundrymen. His own view was that it was deteriorating because sharp, clean castings used to be produced by green-sand whereas today they were not.

Mr. J. M. Midleton (British Steel Castings Research Association) said that he was very interested in the statement on page 5 of the reprinted of the Paper which said: "Further, the surface temperature increases faster in the green mould than in the dried mould. He had determined metal/mould interface temperatures on both sands and found that the temperature at the interface was similar for both types of sand.

Mr. Pettersson, in reply, said in fact he had been a little surprised at the results given in the Paper, but he believed in them, though the measurements should have been repeated more often. Possibly the reason why the previous speaker did not get any difference was that he measured the temperature when metal was in contact with the sand, whereas in his own case it was quite different—the sand was just heated by radiation.

Influence of Moulding Technique

Mr. E. Longden (past-president) said some other very important factors beside the quality of sands were being lost sight of, i.e., the general moulding technique. Large numbers of castings had been made in green-sand and very successfully, too, long before the period of imposing special sand controls. The manner in which the metal entered the mould and the arrangement and control of riser openings were very important matters in the manufacture of medium and large castings. With a large upper mould surface area exposed to rising metal and the riser openings free to the outside atmosphere, the gases generated on this upper surface would flow into the mould cavity and rush out of the risers, very often violently, drawing portions of the top mould surface downwards. The scaling of the riser tops would put the mould atmosphere under compression and force gases to pass out through the sand top and help to prevent spalling and "drawing-in" of the top mould surface.

Mr. Pettersson said naturally he agreed that the technique of pouring was at least as important as the moulding materials, but his investigations had been limited to the moulds—the other side should be left to some other investigator.

On the motion of the CHAIRMAN a very hearty vote of thanks was accorded to Mr. Pettersson for his presentation of the Paper.

Author's Written Comment

After receipt of the transcript of the discussion, the Author elaborated his verbal reply in the following terms:—
Mr. Parkes, when he said that there was no meaning in discussing the effect of an increase in dry- (not) strength, probably had in mind the results obtained with dielectrically-heated test specimens at the British Cast Iron Research Association. According to these there was no increase in strength when the temperature increased rapidly. In his paper he had mostly mentioned the effect of increasing dry- and hot-strength when different moulding sands were under comparison, for instance in discussing the effect of different binders and percentages of binders. In this case, of course, different dry- and hot-strength values would result, and he had pointed out that there was no indication that a high dry- and hot-strength had in itself a negative influence on the spalling resistance. In fact the effect in most cases was positive.

The influence of temperature on the strength of the sand was mentioned in the discussion of the mechanism of spalling, and it was suggested that the strength of the surface layer where the sand was hotter than 530 deg. C., and had already been transformed, was stronger than it would have been at lower temperatures and that this increase in strength might make the sand more resistant against thermal shock than it would have been without this temperature effect. There was, however, in the results of the investigation, nothing that indicated that differences in this temperature effect played any important role in the spalling resistance of normal moulding sands. This was not surprising, as the properties of the expanding sand-layer with temperatures below 530 deg. C. should in all probability dominate the behaviour of the sand.

**Effect of Temperature Differential**

It was also mentioned in the paper that uneven heating of a mould surface might lead to an expansion of hotter parts towards cooler parts and eventually to a rupture in a cooler region. This suggestion was founded on repeated observation and the conclusion drawn, that the cooler parts were weaker than the hotter parts, seemed to be based.

Although it was probably not of vital importance for the theories of the spalling mechanism of sand moulds, this question of the temperature dependence was perhaps worth some discussion. In all high-temperature tests made with the ordinary methods, i.e., with slow heating, a remarkable strength increase had been observed in clay-bonded sands at high temperatures, with a maximum at some temperature between 900 and 1,000 deg. C. With the BCIRA equipment, using rapid dielectric heating, no increase in strength was observed at high temperatures. One must then ask which of these methods gave the true or best picture of what happened in actual moulds. Mr. Parkes had argued that rapid heating obtained with dielectric heating was more similar to the rapid heating of a mould during pouring and said that the strength would increase only after a long heating time. This might be correct, but it must not be forgotten that dielectric heating was not of the same nature as ordinary heating. While with ordinary heating heat always moved rather slowly from the surface to the interior, with dielectric heating the large-scale heat distribution was much more even but in fact there was a great number of small-scale temperature gradients. It is therefore possible that in the first stages of heating, the temperature differences between clay and sand grains might be quite large.

The Author made some direct observations pertinent to this question during this investigation. Moulds which had been exposed to the heat from the molten-metal surface for two minutes or more were often tested immediately afterwards by scratching and poking. The heated mould parts always proved to be much stronger than dry moulds at room temperatures. It was true, however, that two or three minutes was not a very short heating time.

The Author wrote that he wished to stress that, like Mr. Parkes, he believed that a mould could have a good spalling resistance only if its toughness or deformability were high. The results of his investigation, however, indicated that generally a high strength was combined with a fairly high deformability. On the other hand, moulds with low strength might have very good deformation properties and very good spalling resistance.

In reply to Mr. Haynes, the Author said he considered that the "feel" of the sand might tell at least as much as ordinary sand tests about spalling properties. This did not mean that the method of testing by feel was satisfactory, but only that the laboratory tests were very unsatisfactory.

**Modern Materials**

A special conference on "Modern Materials" organized by the Sheet and Strip Metal Users' Technical Association, and postponed from June owing to the rail strike, will be held at the Institution of Electrical Engineers, Savoy Place, Victoria Embankment, London, W.C.2., on October 10th and 11th. Papers include:—"S.G. Cast Iron as a Material for Press Tools" by Dr. A. B. Forrest (Mond Nickel Company, Limited) and "Aluminium-Bronze as a Material for Press Tools" by S. C. Jones (N. C. Ashton, Limited). Further information may be obtained from the Association secretary at John Adam House, John Adam Street, London, W.C.2.

**UK Production Rises**

Between the beginning of 1946 and the end of 1954 the volume of output in Britain rose by 27 per cent, and production as a whole increased by 65 per cent. These figures are contained in a Blue Book published last week by the Central Statistical Office, which also shows that wages in this period increased by 39 per cent, salaries by 50 per cent, income from rents, dividends, and interest by 30 per cent, and income from self-employment by 43 per cent.

The total output of goods and services rose from £9,792,600,000 in 1946 to £12,124,000,000 last year. Manufacturing, mining, building, and gas, electricity, and water accounted for two thirds of this increase.
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from which the "root" of the buckles, i.e., the thin connection between the buckles and the protruded pieces (flats) continued and appeared as burrs or rat tails on two sides of the buckle, sometimes with a low metal fin protruding from the deepest part of the burrow. The size and shape of the buckles could vary very much and it was noticed that the pouring temperature (the bulk) of the metal had a great influence on their appearance. Also buckles obtained with cast iron differed much from those obtained with steel, due to the much greater ability of cast iron to penetrate into and fill small apertures. Most of the other defects would best be characterized as sand inclusions caused by the falling of pieces of a surface layer of the mould. The formation of all the defects could easily be understood as being the result of the spalling (in an early or later stage) of the mould and the more or less complete filling of available space and sometimes also moving of the more or less released sand layers by the rising metal.

VIII: Casting Defects on the Side of Experimental Castings, and Observations relating to Mould Failures in the Drag Part of the Mould (Method A and E)

The bottom surfaces of the experimental castings showed several kinds of burrows (rat-tails, etc.) but very seldom buckles or scabs. One reason for the almost complete absence of the latter defects may be that almost all these experiments were made with steel and the fairly small castings solidified rather rapidly. There was generally a definite relation between the position and direction of the burrows and the paths of the metal streams that entered the mould through two parallel inlets. It seemed as though these surface layers which were heated chiefly by direct contact with the flowing metal expanded in all directions away from the metal streams as an effect of the sudden expansion stresses developed under the metal. At some small distance from the metal the steel became too great and then the mould layer failed by shear. Afterwards the cracks were covered with metal, whereby the casting defects outlined were obtained.

The observations made on cast iron were made in an open mould, made for the study of the side defects, gave the same impression of the yielding of the mould. Moreover it was noted that the mould spalled easily where a vertical part of the mould against which the metal flowed with a horizontal surface. Because of this edge comparatively little resistance was offered against the expansion movement of the surface layer.

REFERENCE


(To be continued)

Improving Utilization of Metals

Cutting costs of production is an essential item in improving or even retaining industry's competitive power and a saving at any stage in a manufacturing process has become of paramount importance. According to a sub-committee of the Institution of Production Engineers, the metal-working industries might profitably examine the effectiveness of their utilization of materials. In a report on the subject the sub-committee states that for a wide range of machined parts the proportion of material converted into salable goods is seldom greater than 70 per cent. and frequently less than 30 per cent.

Considering a not unusual material utilization figure of 33 per cent., the report says that of the original material, two-thirds are machined away and disposed of as scrap at approximately 10 per cent. of its original cost. An increase in material economy in this case to 70 per cent. by no means impossible, would be approximately equivalent to halving the material cost for a part. This is only part of the reduction, however. The machining away of the original material involves labor costs, heat at the machine and in the disposal of the scrap, and absorbs machine capacity and shop floor and handling space.

The sub-committee concludes that it may well pay handsome dividends to spend considerably more energy in purchasing a form of semi-finished material, which is intrinsically more expensive, but closer to the shape and size of finished parts, in order to achieve drastic reductions in further processing.

The annual Park Foundry Horticultural show was held in the works courtyard, Derby Road, Bolsover. The show was opened by Mr. W. A. Ballard (managing director) and the awards were presented by Mrs. Balland.