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Studies on the Solidification and Contraction in Steel Castings - Contraction Stresses.

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SUMMARY

This report discusses the fundamental underlying principles of contraction in steel castings. The following subjects are considered in detail:

(1) Plastic and elastic deformation at elevated temperatures.

(2) Stress centralization.

(3) The magnitude of contraction stresses at hot tearing temperatures and at room temperatures.

(4) Effect of solidification on contraction stresses.

AUTHORIZATION

1. The studies in steel castings were originally authorized by the Bureau of Engineering letter QP/Castings (6-19-Ds) of 13 July 1928.

STATEMENT OF PROBLEM

2. The object of this report is to present information on the nature and magnitude of stresses in cast steel that result from the hindered contraction of the casting.

KNOWN FACTS BEARING ON THE PROBLEM

3. There are four fundamental conditions that make up the underlying principles of a study involving contraction stresses in steel castings. These may be listed as follows:

(1) There are no contraction stresses in a freely contracting cast bar.
(2) In a stressed cast bar the resulting stresses are independent of the length of the bar.
(3) Stress magnitudes vary as to the inverse ratio of its cross-section in which they appear.
(4) Internal stresses in a casting are proportional to its modulus of elasticity, to its coefficient of contraction, and to the differences of temperature involved.

4. In order that the subject of contraction stresses be understood better it would seem advisable to dwell at some length on the above factors effective in stress concentration and stress magnitude.

5. The simplest of all castings is that of a round bar with a uniform section throughout and which is allowed to contract freely.

6. Such a bar would be free from contraction stresses. If, however, the casting were circular in shape, such as for example (Figure 1), contraction stress would be pronounced and their magnitude would largely depend on the rigidity of the inner core of sand. The greater the hindered contraction the greater are the stresses acting on the casting.

7. At any one time during the cooling of this casting from the solidifying temperature to room temperature the stress application on the section ℓ (Fig. 1) is equivalent to

$$S_\ell = E \frac{\Delta \ell}{\ell}$$

where E is the modulus of elasticity of the material and $\Delta \ell$ is the change in length of ℓ that has taken place during the contracting of the steel.

This condition also is true for a longer section L

$$S_L = E \frac{\Delta L}{L}$$

but $L = k\ell$ and $\Delta L = k\Delta\ell$

$$\frac{\Delta L}{L} = \frac{k\Delta\ell}{k\ell} = \frac{\Delta\ell}{\ell}$$

$$\therefore \quad S_\ell = S_L$$

8. Hence, the resulting stresses are independent of the length of the circular bar and no greater in long bars than in short ones. This point is not universally appreciated in the foundry since a casting is seldom made that embodies only those features of uniform section and therefore uniform casting rates. It is a good point to remember, however, as greater emphasis can then be placed on the design of a casting since it is known that the contraction stresses acting on a casting are independent of the length.

9. A slight change in the casting of Figure 1 will bring out other features in the application of stresses. In Figure 2 a large bar of cross-section A_1 is joined to a small bar of cross-section A_2 by heavy end sections. It is assumed that these end sections will prevent the casting from movement so that it cannot bend or warp. Bar A_2 will completely solidify before the large Bar A_1; thus a temperature gradient is produced within the casting. This temperature gradient is responsible for a setting up of stresses in the casting since this amount of solid contraction depends on the temperature and the hindered contraction. As the two bars are joined together, and are therefore not allowed to contract freely, a compression stress will be developed in the large A_1 bar and a tension stress in the small A_2 bar. Since the stress system must be in equilibrium, the following conditions are obtained:

$$S_t A_2 = S_c A_1$$

S_t = tension stress

S_c = compression stress

or

$$\frac{S_t}{S_c} = \frac{A_1}{A_2}$$

10. It is thus shown that the magnitude of the stresses is in an inverse ratio to the size of the cross-section in which they appear.

11. This general line of reasoning can be carried out more fully as has been done by Heyn (1)* to show the relationship of the internal stresses to the solid contraction.

12. Again referring to Fig. 2 when the bar with the cross-section A_1 has completely solidified at temperature t_1 the smaller bar, cross-section A_2 has already solidified and is at a lower temperature t_2, and therefore has been contracting. If both bars were free and not held together by the heavy connecting section, bar A_2 would assume the length

$$L = \ell \left[1 - \alpha (t_1 - t_2) \right]$$

where ℓ is the original length of the bar upon complete solidification and α is the coefficient of contraction. Since the bars are held together by the heavy sections the two bars must have a mean length ℓ_h, and the large bar A_1 would be under tension stress S_t and the small bar A_2 under a compression stress S_c, with the conditions of equilibrium as follows:

$$A_2 S_t = A_1 S_c \qquad (1)$$

$$S_t = E \left[\frac{\ell - \ell_h}{\ell} \right] \qquad (2)$$

$$S_c = E \left[\frac{L - \ell_h}{\ell} \right] = - E \left[\frac{\ell_h - L}{\ell} \right] \qquad (3)$$

where E is the modulus of elasticity of the steel, and the stresses do not exceed the elastic limit.

But $$L = \ell \left[1 - \alpha (t_1 - t_2) \right] \qquad (4)$$

By substituting values of equations (2), (3) and (4) in equation (1) it follows that

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*Numbers refer to references listed in the Bibliography

$$\ell_h = \ell \quad \frac{\left\{A_1 - A_2 \quad \left[1 - \alpha \ (t_1 - t_2)\right]\right\}}{A_1 - A_2} \qquad (5)$$

Putting the value of ℓ_h in equations (2) and (3) it is found that

$$S_t = \frac{E \ A_2 \quad \alpha \ (t_1 - t_2)}{A_1 - A_2} \qquad (6)$$

$$S_c = \frac{E' A_1 \quad \alpha \ (t_1 - t_2)}{A_1 - A_2} \qquad (7)$$

13. From the equations (6) and (7) it can be readily seen that the internal stresses are proportional to the modulus of elasticity, to the coefficient of contraction, and to the difference of temperature.

14. So far it has been assumed that the bar shapes have undergone changes of only an elastic nature. As long as the internal stresses cause only elastic deformation, the stresses will be temporary; however, when permanent deformation exists then permanent stresses are left in the metal.

PLASTIC DEFORMATION

15. The casting as presented in Fig. 2 will again be considered. Because of the difference there exists between the diameters of bars A_1 and A_2 they will cool from the solidifying temperature to room temperature at different rates. Thus at any definite time during cooling, the temperatures of the two bars will be different. The temperatures will, however, approach each other and equalize at room temperature or perhaps at some elevated temperature. Fig. 3 represents a typical curve showing the unequal cooling conditions of the two bars. It will be noticed that the differences will be the most pronounced at the higher temperatures. It has already been pointed out that the temperature differences of the two bars create internal stresses, which in this case, are so great that the elastic limit of the material is exceeded. To exceed the elastic limit is not a very difficult condition to fulfill since steel at very high temperatures has exceptionally low elastic limits and all deformation taking place is principally plastic.

16. The mold chilling effect and the variation in cross-sectional areas cause the wide difference in temperature. Since the contraction of the steel is closely aligned with the temperature the normal rate of contraction of the two bars will be somewhat different. A possible condition that may exist is shown in Fig. 4. The data plotted here represents the time-contraction characteristics of each bar separated instead of being joined together by the flange construction. Here again the most noticeable variation comes shortly after the steel has solidified. As this portion of the curve is rather interesting, it is enlarged as in Fig. 5.

17. It will be supposed that the flange joined bars have plastically deformed at a definite time t_1 and that the lengths of the bars have compromised on a mean length B so that at the definite time t_1 the large diameter bar has been plastically compressed by the amount CB and the small diameter bar has been plastically stretched by the amount DB. Thus at t_1 the two bars have the same length but are at different temperatures. Now as the cooling time proceeds from t_1 the bars continue to contract and elastically deform so that at the time t_2 the tendencies for the respective lengths are represented by the lines BE and BF where BF corresponds to the contraction of A_2 and BE corresponds to the contraction of A_1. These lines indicate the extensions which could take place after passing time t_1 if the bars were separate instead of being coupled. At time t_2, then, the bars tend to differ by an amount FE, and they compromise at the mean value B′. Thus, the large diameter bar A_1 is in compression corresponding to the amount B′E while the small diameter bar A_2 is in tension corresponding to the amount B′F.

18. The above conditions do not represent entirely the actual conditions found in the cooling of steel. For one thing, there is no clear cut temperature at which deformations change from the plastic to the elastic state. In fact experimentation has shown that stresses causing initial yielding at low temperatures decreases about linearly with increasing temperature, but become nearly independent of the temperature when the melting point is approached. Thus metal crystals have a small but finite elastic limit at temperatures approaching the melting point.

19. Conditions presented in Fig. 5 do, however, correspond most closely to conditions encountered in practice and explains the presence of permanent stresses within the casting.

20. In the preceding paragraphs, the discussion was limited to stresses that were developed because of cross-sectional differences in the metal casting. It should also be pointed out that the mold conditions can cause stress conditions similar to those above. The manner in which mold conditions operate to bring about internal stress has been enumerated many times by authors writing on the subject of the Design of Steel Castings. It is therefore sufficient to say that internal stresses arise due to the prevention of normal contraction by the rigidity of sand molds and cores. It has been shown in a previous paper (2) in this series that the universally used "patternmakers shrinkage" is not the normal free contraction of steel and that castings manufactured on this basis have, in the as cast condition, internal stresses present.

21. It may be helpful if further consideration were given to an actual case involving stress application due to mold resistance. A bar with a flange on either end molded in a hard dry sand may suffice as an example. It is evident that the sand between the two flanges will prevent the bar from contracting normally. The bar tends to contract toward its center but the sand pressing against the inside faces of the flange prevents it from so doing and hence stresses are built up in the casting, the bar portion being under a tension stress.

22. Now one of two things can happen; (case 1) either the casting tears at the junction of the bar to the flange, or (case 2) it cools to room temperature in one piece but its overall length is much greater than that of a plain bar without flanges.

23. Why should the casting tear as suggested in case (1)? The tension stress that was developed in the bar by the flanges will concentrate at the weakest section, which in this case was the junction of the flange to the bar. The stress was so great, since the hard mold prevented any movement of the flanges, that plastic deformation could not take place rapidly enough and consequently the physical properties of the metal were exceeded and hot tears formed.

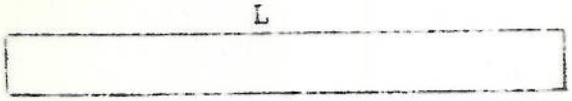
24. In case (2) it is evident that stress centralization did not occur in the magnitude of case (1) since the casting did not tear. But the casting was hindered from contracting normally and hence was under stress, as has been conclusively demonstrated (2). The magnitude of this stress depends on the rate of the stress application, or to put it in another way, the stress depends on the rate of plastic deformation.

$$S = K \frac{d\rho}{dt}$$

where S is stress and ρ is the plastic deformation, or elongation, or if one prefers, the hindered contraction.

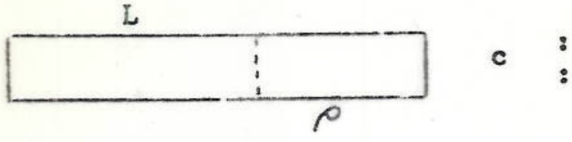
25. Perhaps a diagrammatic representation of the principles involved would present the case more clearly.

I. Length of the bar immediately after solidifying.



II. Length of the bar at t° C when contracting freely.

III. Length of the bar at t° C when hindered from contracting freely.



26. In diagram (I) the bar takes on a definite length corresponding to the dimensions of the mold. If the bar were then allowed to contract freely its length would be as illustrated in (II) wherein c represents the amount of free contraction. If, however, the bar were not allowed to contract freely, such as has been done above where flanges were placed on the ends of the bar, then ρ would represent the amount of elongation or plastic deformation that has taken place. The magnitude of ρ depends on the amount of stress acting on the bar and the time in which it is effective. Plastic flow of a metal occurs only as long as there is a force acting on it and the rate at which it takes place depends on the magnitude of the force. Thus, when metal is cast under conditions that tend toward high resistance to

contraction, the magnitude of the stresses acting on the casting is high, the rate at which they build up is fast, and the amount of plastic deformation that takes place is large. If, however, the resistance to contraction is not high, then the other factors bearing on it will be correspondingly lower.

27. The above has been set forth to explain some of the more important points of plastic deformation. It should be added that if at any time the cooling cycle of the stressed casting could be arrested, at some high temperature, the magnitude of the stress would be progressively less with time, since plastic deformation of the metal would reduce the stress to zero. From this it can be seen that the cooling rate of the metal is important in considering the magnitude of the stress. In two hindered contracting castings acting under like conditions, except for the cooling rate, the fastest cooled casting will build up the highest stresses.

STRESS CENTRALIZATION

28. It was stated under the discussion of the flanged bar above that the casting would tear at the junction of the bar and the flange. The reason for this is two-fold: (1) this section is at the highest temperature and therefore the weakest since it was the last point in the casting to solidify; and (2) corners are excellent points of stress centralization. All abrupt changes in section, sharp corners and casting irregularities are potential positions of stress concentration. When stresses arising from hindered contraction of a large casting concentrate at one point, it is easy to see that stresses may build rapidly. It is because of this condition of stress centralization that many foundrymen have looked skeptically at the statement made previously that contraction stresses arising in a casting are independent of the casting length since they are able to point to the fact that many long castings fail while short castings do not. This failure in long castings is not the result of greater stresses developed because of their length, but it is due to the fact that these stresses may centralize in one place due to hot spots, sharp corners, et cetera., and the combined stresses centralized in a long casting will be much greater than the combined stresses centralized in a short casting.

29. How is it possible to prevent stress centralization? Proper casting design will limit the concentration of stresses. Castings should be so designed that they will embody the minimum number of abrupt changes in section, sharp corners, skin irregularities, and isolated hot spots. Brackets are used to a considerable degree today to distribute stresses from sharp corners over a thin web of steel that has quickly solidified, and hence, because of its greater strength, would absorb the stresses, preventing casting failure. Brackets are, however, not always successful, for in the final analysis they add but little strength to the casting and at best are weak tie rods to adjoining sections, since the brackets themselves are at the same temperature as the skin of the casting. A judicious use of good casting design principles is by far the best method of preventing centralization of stresses.

30. In the preceding pages, it has been pointed out that contraction stresses may result from the differential cooling of metal sections and from the action of the mold hindering the normal casting contraction. It should be stated that there may be a combination of both stress forming methods arising within the casting.

THE MAGNITUDE OF CONTRACTION STRESSES AT HOT TEARING TEMPERATURES.

31. Probably the most serious defect with which the steel casting manufacturer contends are cracks, and of these the hot tear crack is the most prevalent. Prior to 1928 much had been said concerning the cause of hot tearing and how to prevent it, but little was known of the actual conditions of hot tearing, such as the cracking temperature or the magnitude of the stresses causing hot tearing. In 1928 Körber and Schitzkowski (3) produced hot tears in flanged bars by hindered contraction and decided that the critical temperature at which hot tears are most liable to be formed was about 1250 to 1300 degrees Centigrade (about 2280 - 2370° F.). They did not, however, measure the stresses on the bars at the time of hot tearing. In 1932 the author and Mr. Gezelius made a study of the stress acting on a bar during hindered contraction. These bars did not break under the hindered contraction applied as they were so designed as to prevent points of stress centralization. Since the bars did not break this work did not show the actual amount of stress necessary to cause hot tears at the hot tearing temperature, but it did show the load carrying ability of steel under hindered contraction.

32. In 1936 Mr. Hall at Woolwich Arsenal (4) presented data on the strength and ductility of steel at temperatures near the melting point. In the region of 1250 to 1300 degrees C he showed that the ultimate stress necessary to cause failure in one inch bars averaged, for cast carbon steel, from 1700 pounds per square inch at 1300° C. to 2500 pounds per square inch at 1250° C. There is no indication from this work that the temperature range, 1250 to 1300° C. is more conducive to the formation of hot tears than any other temperature range. In fact the temperature-ultimate stress curves show nearly a straight line relation in that there is practically a uniform increase in the ultimate strength as the temperature drops.

33. A stress of 2000 pounds per square inch is quite large considering that in the case of cracked castings it presumably is developed by hindered contraction.

34. It was shown in the second and fourth publications of this series (2)(5) that in a 0.35 percent carbon steel in the temperature range 1300 - 1250 degrees Centigrade, the amount of stress developed on a bar of 2 square inches with various types of hindered contraction was as follows:

Stress, pounds/sq.in.		Type of Hindered Contr.	% contr. at Room temperature.
1300° C.	1250° C.		
230	350	E spring	1.7
500	700	G spring	1.0
700	1000	C spring	0.5

35. The above figures would indicate that even under the most drastic conditions of hindered contraction the stresses developed during the 1300 - 1250° C. temperature range would not be sufficiently high enough to cause failure since Mr. Hall shows evidence of ultimate strengths in the neighborhood of 2000 pounds in this temperature range. Notwithstanding all this it is known that castings do fail and the hindered contraction that is active

may not be much greater than that developed by the E spring as listed above. The realization of this fact leaves two points for consideration; either the critical cracking temperature has been selected at too low a temperature, or else stress centralization is responsible for the apparent discrepancies so that tearing does occur when most of the casting cools to the 1250 - 1300° C. critical cracking range.

36. A study of hot tear fractures as they actually occur in the foundry will show that there has been little or no elongation or reduction of area of the steel prior to fracture. Mr. Hall has shown that all the steels he tested had an elongation value at skin temperatures below 1300° C. In some of the low carbon steels (below 0.15% carbon) ductility, as measured by elongation, was found to exist at temperatures approaching 1400° C. In fact all the steels he studied had a 5% or greater elongation when fracture occurred at 1250° C.

37. If these points are considered it would seem reasonable that the critical cracking temperature range was above 1300° C., perhaps between 1300 and 1400° C.

38. In a study of the tensile strength at elevated temperatures of cast steel, that had previously cooled to room temperature, Piwowarsky, Božić and Söhnchen (6) reported tensile strengths of 250 to 300 pounds per square inch at 1250° C. These figures are more in line with the stresses developed by hindered contraction, but it is felt that not too much significance should be placed on Piwowarsky's figures since the rate of testing was considerably slower than that used by Hall and temperature gradients as are usually found in castings were not present.

39. It was suggested that perhaps, because of stress centralization, tearing occurs when most of the casting cools to the 1250 - 1300° C. range. It is quite possible that such may be the case since, as has been shown, differential cooling and hindered contraction due to the mold will set up stresses that will concentrate at a hot spot in the casting with the result that the casting will tear. The hot spot may have a temperature approaching 1400 degrees C. while other parts of the casting will be at temperatures of 1250 to 1300 degrees Centigrade. In such a situation, stresses of 250 pounds to 500 pounds per square inch could arise through hindered contraction which, if concentrated at the 1400 degree hot spot would be, according to Hall's experiments, a sufficient load to cause tearing.

40. Thus, it is possible that small tension stresses as developed by hindered contraction are responsible for hot tear formation providing that the hindered contraction present is greater than that normally allowed under "patternmakers shrinkage".

41. A study of hot tearing as exhibited in various castings is responsible for a realization that tearing in some cases takes place when the responsible stresses are even lower than that which appears to be necessary to cause failure by tension. It is often evident that failure has been due, from the very nature of conditions involved, to shear stresses. For example, Figure 6, shows a small casting made in green sand that consisted of 4 one inch diameter bars having been run from a larger block section. The bars were 30 inches long and free at the end. It will be noticed that the two outside bars were completely torn away from the block where the two inner

bars were solid to the block and had to be cut from it. The bars contracted towards the block and the block contracted towards its center. The hindered contraction due to the green sand was necessarily low, yet the shear stress developed, because the contracting of the block, was sufficient to cause the outer bars to be torn from the block. From the very nature of things, it can be seen that the resulting shear stress was very low. This would indicate that steel at these very high temperatures has very little resistance to shear stresses, in fact, much less resistance than it has to tension stresses. Hot tearing is not so much a result of tension stresses as it is a product of shear stresses. If such is the case, an entirely different light is brought to bear on the problem and a knowledge of the properties of steel under tension would not therefore show the magnitude of the stresses causing hot tear formation. Some attempt to increase the knowledge along this line is undoubtedly necessary. It should be added, however, that the entire problem of stress magnitude at the time of hot tearing is undoubtedly tied up with (1) the rate of stress application, (2) the centralization of stresses, and (3) the nature of the acting stress.

42. Before leaving the subject of stress magnitude at high temperatures, it might be well to call attention to a question that is often stated as follows: In order to relieve casting stresses, it is necessary to heat the casting to fairly high temperatures. In view of this fact, why is it that there is any stress at all on the casting at these high temperatures? The answer is obvious in that the casting sections are continually in stress under hindered contraction conditions. Though plastic deformation does take place to relieve this load, the time that the casting remains at any one temperature is not sufficient to allow for a complete equilibrium of conditions to be obtained; hence, the casting sections are always under stress.

MAGNITUDE OF STRESS AT ROOM TEMPERATURE

43. A very definite estimate of the magnitude of stresses that may be found in steel castings has been presented in the second and fourth reports of this series (2 and 5). These investigations presented in detail the stress conditions acting on various carbon and alloy steels under hindered contraction. Summarizing this work in a very general manner the following conditions are found to prevail on a section of a cross sectional area of 2 square inches at room temperature:

% Hindered Contraction	Stress, pounds per square inch
0.5	11,000
1.0	7,000
1.7	2,700
2.4	0

44. If a casting contracts only one percent during cooling from its solidification to room temperature, then a stress of approximately 7,000 pounds per square inch will be acting on the casting due to hindered contraction alone. If, however, the casting is removed from the mold, hindered contraction can no longer be effective, and the stress due to hindered contraction is removed. For example if a flanged bar cooled in a hard mold so that at room temperature it had contracted only 1 percent a stress of

7000 pounds per square inch would be acting along the bar due to the action of the mold exerting a force against the inside faces of the flanges. If the sand is removed, the force is removed, and the casting is no longer under stress from hindered contraction. This does not necessarily mean that the casting is entirely free from stress. It may have locked up stresses that are present in large magnitudes. This fact is well known from practical observations of two types. Large castings that have been shaken out and allowed to remain on the foundry floor have cracked badly if the room temperature has dropped considerably. In another case, castings that have been pickled may show surface cracking caused by high stress conditions (7). These high stresses are developed by unequal cooling of the metal sections. One section may be expanding during the critical range while another section is contracting. This may mean a difference of as much as 0.3 percent movement as according to charts prepared in the 2nd and 4th reports (2)(5). Since these sections are tied together, movement is not possible; hence, stresses of large magnitude are tied up within the casting. If 30,000 pounds per square inch was assumed as the elastic limit, an assumption which is not at all unreasonable, and the modulus of elasticity 30,000,000 pounds, then a resistance to a movement of 0.1% would be equivalent to a stress equal to the elastic limits at room temperature conditions. This would be somewhat different at critical range temperatures but a general indication is given of the stress magnitudes that may exist when there is a resistance to contraction or expansion of 0.3% at critical range temperatures.

45. There are two methods by which it is possible to prevent locked up stress from reaching such high magnitudes. One method necessitates the use of casting design, or controlled solidification to prevent sections from having such wide temperature variations. The other method is to produce castings with alloy combinations that show only a small expansion during the critical range. This latter method has been used in a practical way with good results. A manufacturer found that he was having difficulty in producing a certain casting because of cracking at apparently low temperatures. He changed to a molybdenum cast steel, because its expansion during the critical range was very low, and produced perfect castings.

46. From the above discussion it can be concluded that a casting in the mold at room temperature may be stressed as much as 10,000 pounds per square inch by hindered contraction due to mold conditions. The casting may also be under stresses the magnitude of which may mount as high as the ultimate tensile strength of the steel and in this case the residual stresses are caused by temperature gradients.

47. Considerable information on stress characteristics may be learned from a continued study of the ordinary commercial casting, especially if it shows failures due to cracking. The location of the crack would give indications of the manner in which the stresses operated. A simple casting whose cross-section had the appearance as illustrated in Fig. 7, may be used as an example. A large number of castings have such a type cross-section only perhaps in more elaborate details.

48. Suppose (Case 1, Fig. 7) sections C and C' are found torn away from Section A, then it may be correctly assumed that real hard cores were used at E and E' causing hindered contraction, load application, and plastic

deformation due to temperature gradients in varying sections, and finally stress centralization resulting in a shear stress causing cracking. Section D did not break from A because it is cooled at somewhat the same rate as A. However, B might break from D such as C did from A. If, however, (in Case II, Fig. 8) cores E and E' were very collapsible and stresses were not formed by hindered contraction due to core resistance, then it is quite possible that a tear will be found where D joins A. In this case, Fig. 8, stresses are built up by hindered contraction due to metal section differences. Sections C and C' are cooling faster than section D and consequently contracting more than Section D; thus sections C and C' are under tension while D is under compression stresses. The tear occurs at the hot spot which is the junction of the sections D and A.

49. Suppose, however, the castings as illustrated in figures (7) and (8) cooled to room temperature without cracking. It was found by experimentation that by cutting section D (Case II), the gage length marked in this section increased and it was necessary to apply a load of 1,000 pounds to return the gage length to its former length. This indicates that a compression stress of 1,000 pounds was acting on section D when the casting was at room temperature.

50. Section D in Case I was given a like treatment but it was found that the gage length did not move to a measurable amount and the casting presumably was without stress. This showed that all sections of the casting plastically deformed and when the casting was removed from the mold, the stresses due to mold resistance were relieved and the casting apparently free from stress. (The word "apparently" was inserted because the experiment did not measure the stresses in section A or section B).

51. It might be worth pointing out that it is practically impossible to produce even a freely contracting round bar that is completely free from internal stress due to temperature gradients. Since such a bar cools from the outside toward the core, circumferencial tension and compression stresses are always present.

52. The above experiments point out that if a stress analysis is made of castings, more familiarity with casting stresses can be obtained.

EFFECT OF SOLIDIFICATION ON CONTRACTION STRESSES.

53. At several places in the preceding discussion, mention was made to hot spots within castings and the part they played in the centralization of stresses. It was also suggested that if these hot spots could be eliminated a casting would be less subject to hot tear formation. By controlled directional solidification, castings may be produced so that no adverse temperature gradients and hence no pronounced hot spots will be formed. Since large adverse temperature gradients are potential stress formers, anything that can be done to reduce adverse temperature gradients within a casting would likewise reduce the stresses acting on the various sections of the casting. Other investigators have reported the difficulty that arises from trying to form hot tears in castings that have a uniform cooling rate. Thus castings that have a controlled directional solidification not only are more properly fed but are less prone to hot tear formation.

54. Besides eliminating hot spots and reducing adverse temperature gradients, there is also the possibility that a casting produced by controlled directional solidification may be subject to lower hindered contraction stresses due to mold resistance than are found in the same casting produced by the orthodox solidification methods.

55. For example, a pattern was designed that would be subject to considerable mold resistance and castings were produced by the orthodox manner and by Batty's partial reversal controlled directional solidification method. Figure (9) shows a plan view of the pattern and Figures (10) and (11) illustrate the two methods as molded. The directional solidification casting was rotated through an angle of 30 degrees immediately after pouring. The castings were sectioned and it was found that both methods produced solid castings.

56. Accurate measurements were taken as to the amount of contraction that took place; these are listed as follows:

Casting Conditions	Mold Conditions	% Contraction	Hindered Contraction lbs/sq.in.
Orthódox	Dry sand	1.06	5700
C.D.S.*	Dry sand	1.29	4350
Orthodox	Green sand	1.56	2975
C.D.S.	Green sand	1.59	2800
C.D.S.	Green sand, furnace cooled.	2.26	--

* Controlled directional solidification.

57. The column "Hindered Contraction, lbs/sq.in" was obtained from the curve, Fig. (12) drawn from data presented in the second report of this series (2) and is included to show the general nature of the stresses that can be obtained by hindered contraction due to mold resistance at the time the casting is at room temperature and still within the mold.

58. It may be noticed from the table that in the dry sand practice the two casting methods had rather widely spread contraction results. The reason for this is that in the orthodox method a more liberal use is made of feeding heads. These protuberances increase the surface area of the casting, and act as extended flanges with the result that there is more mold resistance on the casting and hence the casting has less opportunity to contract. The orthodox casting including heads and gate weighed 40 percent more than the controlled directional solidification casting.

59. When the two casting methods were produced in green sand there was very little difference in their total contraction and the stresses developed were roughly a half of those attained when the dry sand practice was used.

60. If a casting is shaken out of the mold soon after pouring and placed in a heated furnace and slowly cooled to room temperature, then contraction values equivalent to a freely contracting bar can be obtained, and the casting would be practically free from all types of contracting stresses.

61. It therefore may be said that the method of solidification influences the action of contraction stresses.

BIBLIOGRAPHY

1. E. Heyn, "Metallographie", Leepzig - G.J. Coschen 1909.
2. C. Briggs and R. Gezelius, "Studies on the Solidification and Contraction in Steel Castings II - Free and Hindered Contraction of Cast Carbon Steel", Report No. M-1075 of 20 September 1934 to the Bureau of Engineering and Bureau of Construction and Repair, Navy Department.
3. F. Körber and G. Schitzkowski, "Beitrag zur Schwindung von Stahlguss", Stahl und Eisen, (1928) pp. 129.
4. H. Hall, "The Strength and Ductility of Cast Steel During Cooling from the Liquid State in Sand Moulds". Second Report of the Steel Castings Research Committee, The Iron and Steel Institute, Special Report No. 15, 1936, p. 65
5. C. Briggs and R. Gezelius, "Studies on Solidification and Contraction in Steel Castings - The Free and Hindered Contraction of Alloy Cast Steels". Report No. M-1229 of 13 January 1936, to the Bureau of Engineering.
6. E. Piwowarsky, B. Bŏzić, and E. Sohnchen, "Zugfestigkeit und Eischnurung von Stalhguss bei 650 bis 1450° C.", Archiv. fur das Eisenhuttenwesen, 1933-34, Vol. 7, p. 127.
7. C. Briggs and R. Gezelius, "The Pickling of Steel Castings", Report No. M-1047 of 17 April 1934, to the Bureau of Engineering.

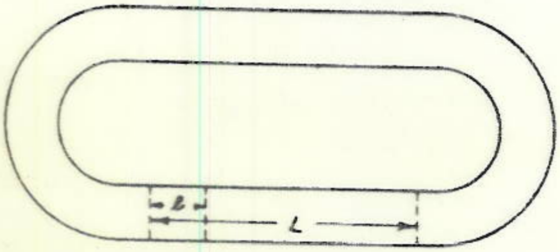


FIG. 1

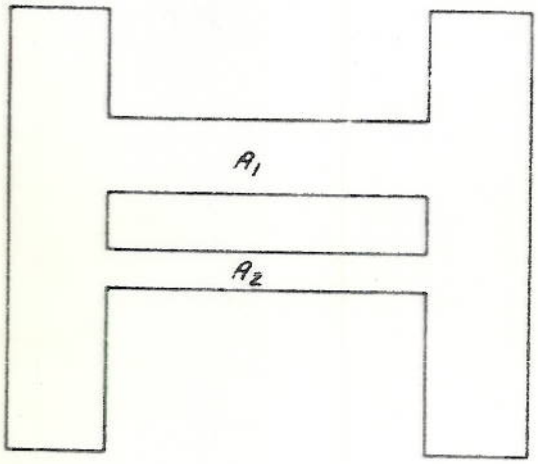


FIG. 2

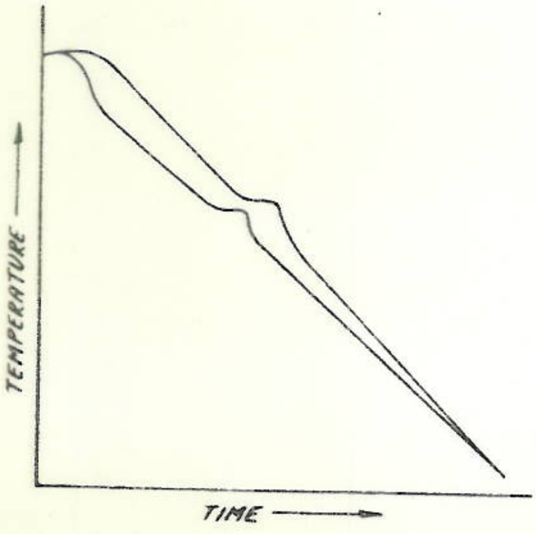
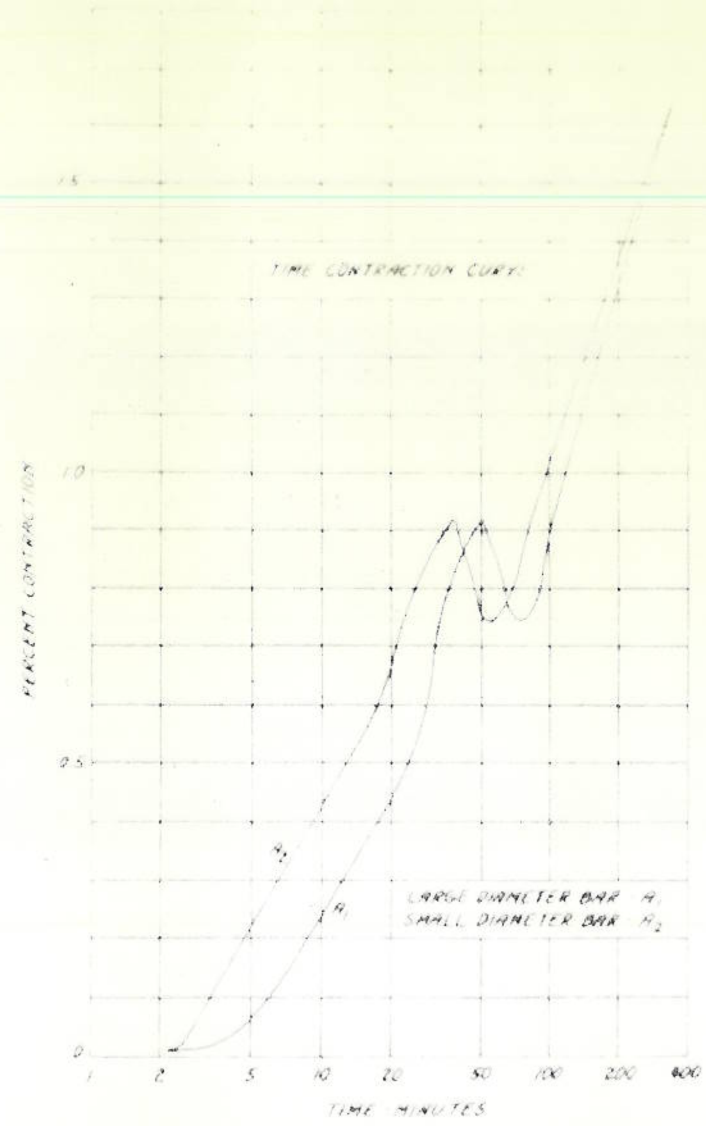


FIG. 3

PLATE I

PLATE C



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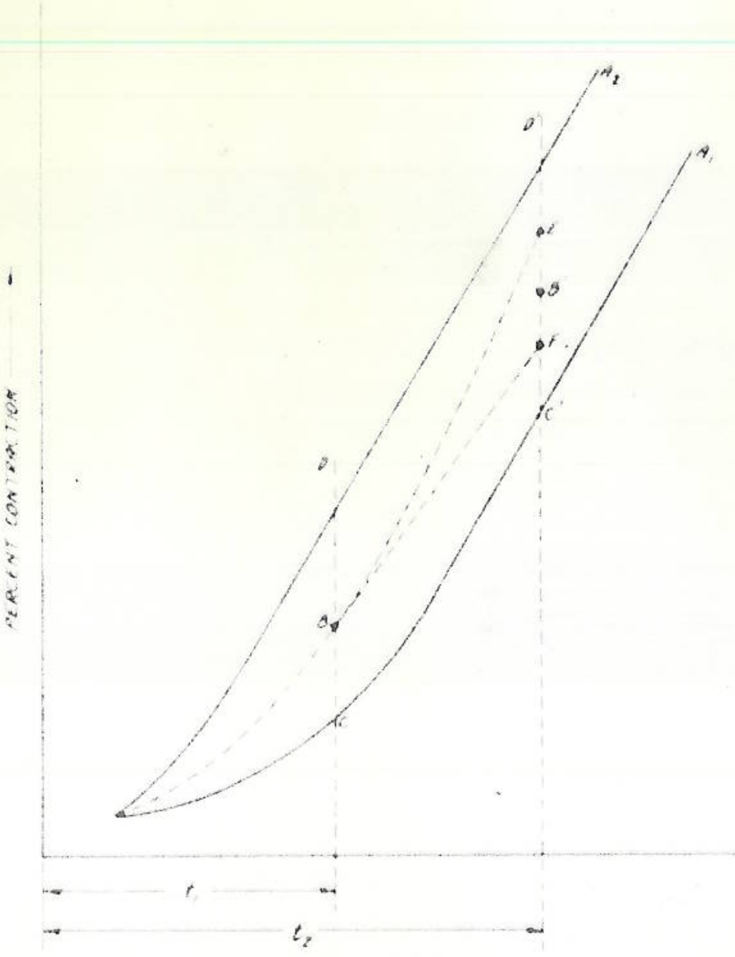
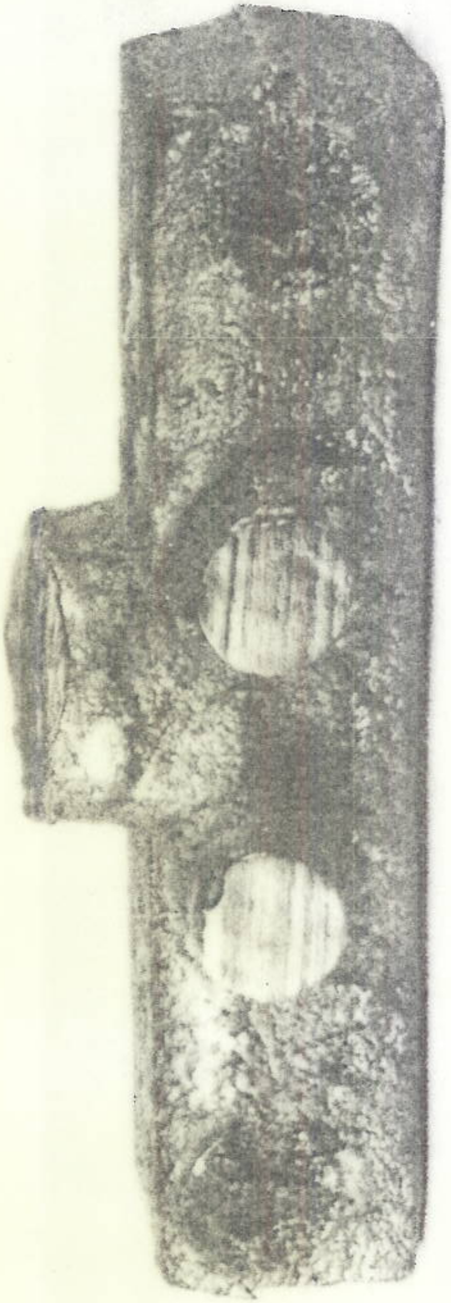
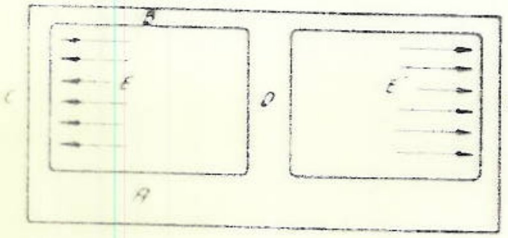
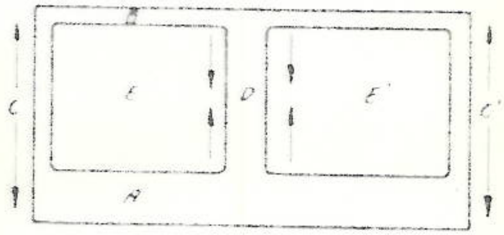


FIG 5





CASE I - FIG 7



CASE II - FIG 8

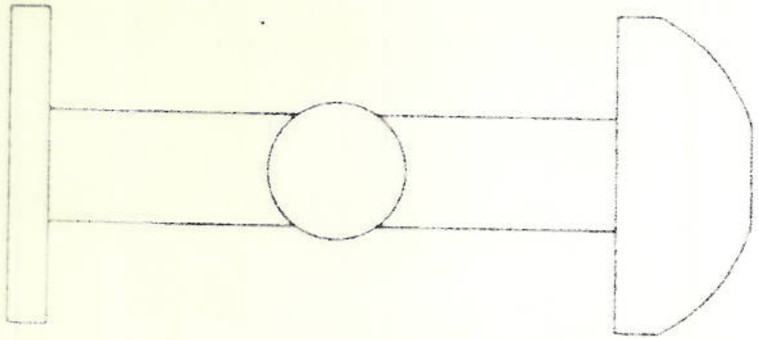


FIG 9
SCALE 1/6

PLATE 4

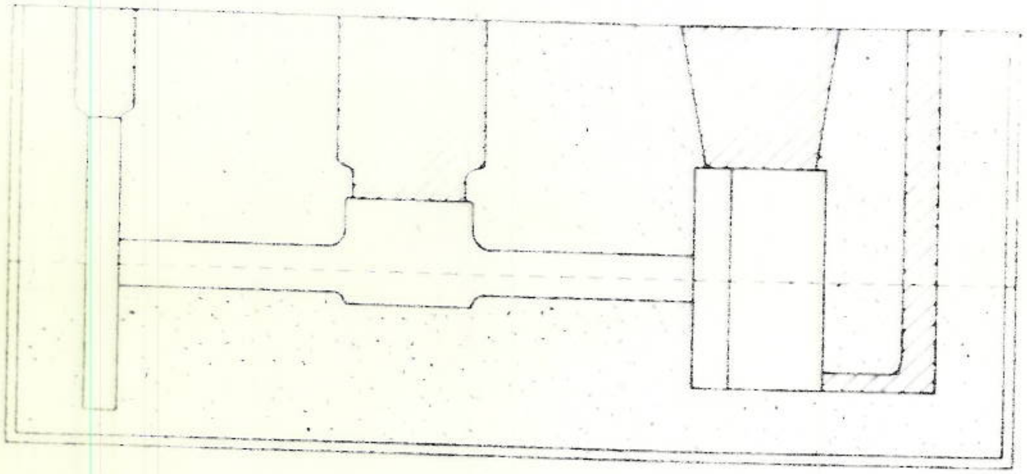


FIG 10

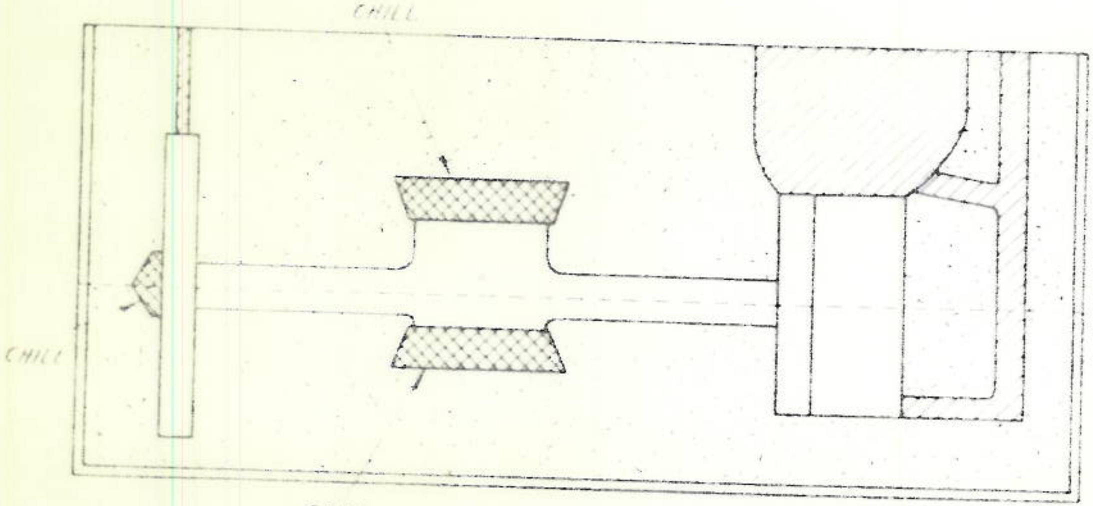


FIG 11

PLATE 5

STRESS ON 0 35% CARBON STEEL
AT ROOM TEMPERATURE

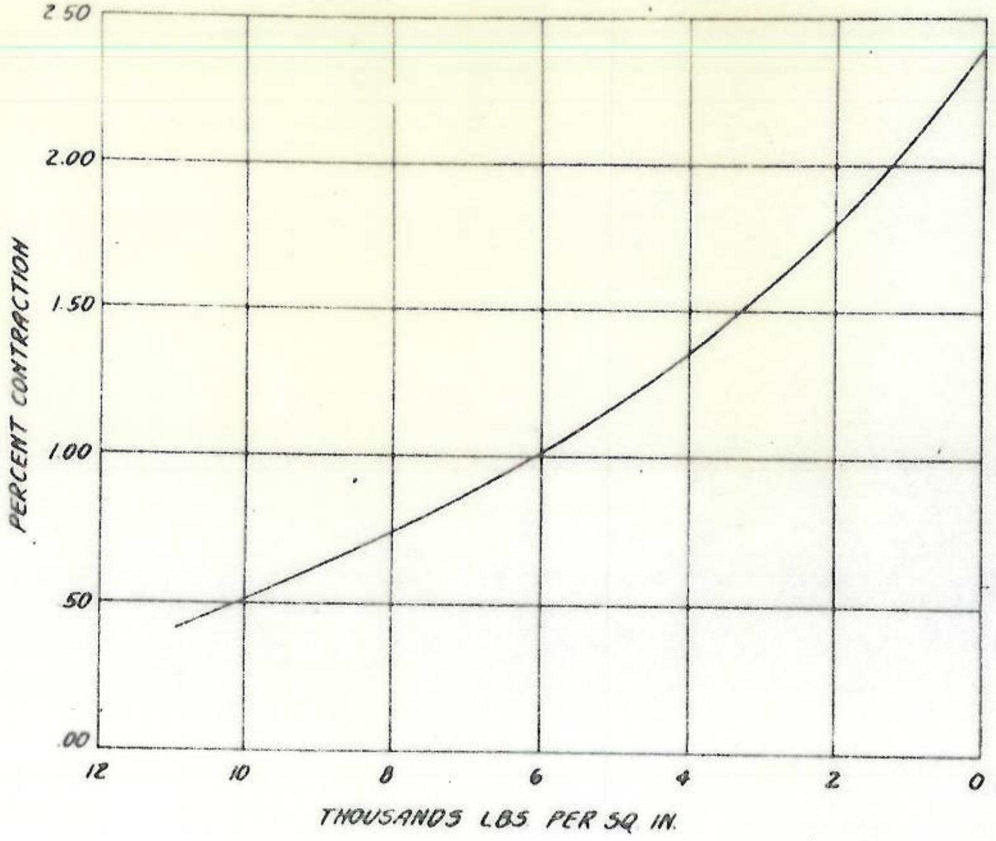


FIG. 12

PLATE 6