Nov. 12, 1957 E. M. MacCUTCHEON, JR 2,813,049

METHOD FOR PREVENTING RUPTURE OF METAL STRUCTURES

Filed Jan. 9, 1953 2 Sheets-Sheet 1

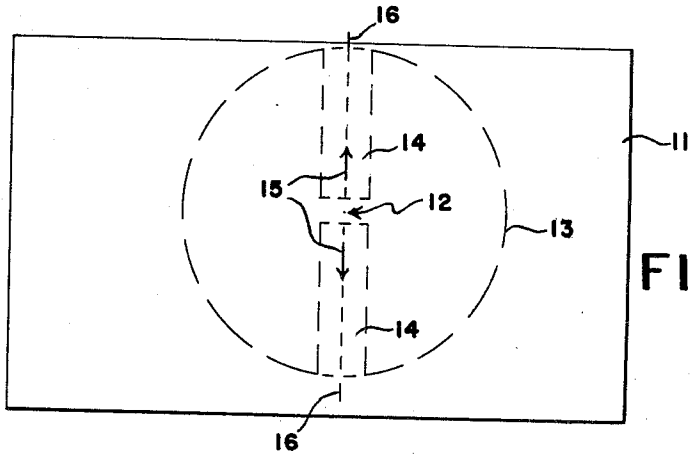


FIG. 1

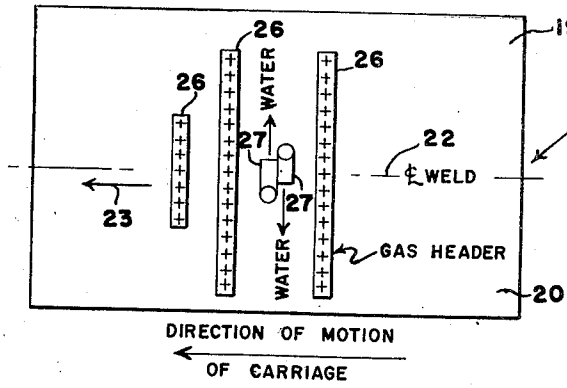


FIG. 2

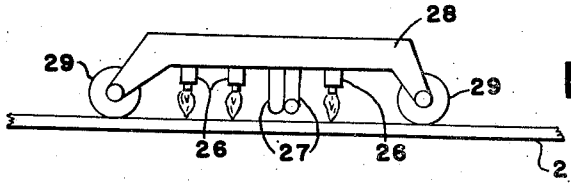


FIG. 3

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2 Sheets-Sheet 2

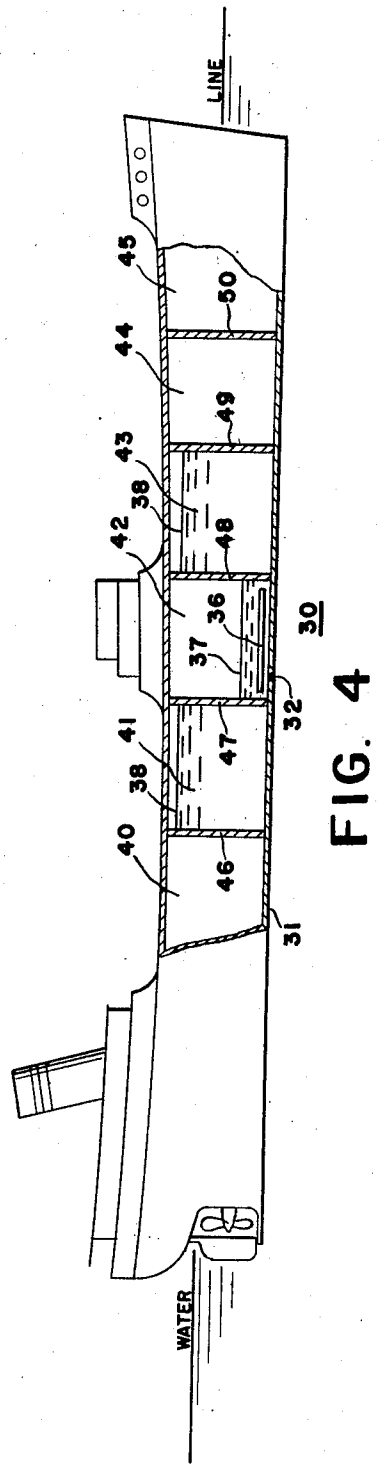


FIG. 4

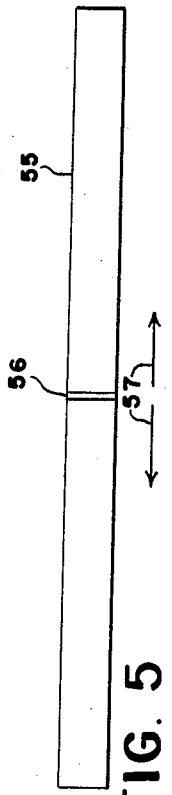


FIG. 5

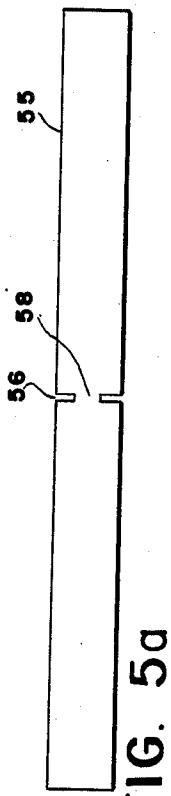


FIG. 5a

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METHOD FOR PREVENTING RUPTURE OF METAL STRUCTURES

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6 Claims. (Cl. 148—12)

(Granted under Title 35, U. S. Code (1952), sec. 266)

The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

The present invention relates to methods of preventing ruptures of metal structures and more particularly to methods of treating such structures by the application thereto of heat or mechanical stresses which treatment improves the toughness of the structures.

Occasionally metal structures fail by rupture. Ruptures can be classified conveniently as brittle, intermediate, or ductile. Ruptures of the brittle type usually are called cracks and are the most common and the most dangerous. Bridges, oil storage tanks, trucks and machinery, all have ruptured. Recently the cracking and breaking-in-two of several ships attracted widespread attention. The ship failures highlighted the need for a rupture preventive which would reduce the jeopardy to metal structure of rupture.

Ruptures are not the result of one cause alone. Instead, the essential contributing causes are three in number, viz.; load, brittleness of the metal, and notches.

Loads contributing to rupture in ships stem in part from service conditions such as cargo distribution or ocean waves. However, the load includes also those locked-in stresses which increase the chance of rupture.

Brittleness of the metal is an important cause contributing to rupture. Brittle metals rupture more readily than ductile metals. Some metals are sensitive to temperature and are more brittle at lower temperatures. Steel is one of the temperature sensitive metals. Steel often changes its rupture performance from ductile to brittle as the temperature drops over a range of only a few degrees (often less than 20° F.). The range of temperature over which the rupture performance changes from ductile to brittle is called the transition zone. Ductility and brittleness can be expressed in terms of the energy absorbed by the metal as the rupture progresses.

A notch is a discontinuity in the metal of a structure. Examples of notches are re-entrant corners where parts are joined, cuts in plate edges or cavities in welds. Thus a poor design geometry can be a notch. A notch can result also from faulty workmanship such as irregular torch cuts or defective welds. Recently defective butt welds in ship hulls have been prevalent crack sources. Of equal importance are the so-called metallurgical notches resulting from discontinuities in the metallurgical structure of the base metal, the weld or the heat affected zone next to the weld. In many cases close examination shows that the so-called metallurgical notch actually contains macroscopic or microscopic cracks such as can be found about an arc strike on medium carbon steel. However, such cracks are not known to be an essential characteristic of metallurgical notches.

Notches bring about three harmful influences. First, they magnify the stresses and strains locally. Second, they create a complex state of stress in which the metal is pulled in all directions at once. This is bad because the metal cannot flow locally and adjust itself. Third, and last, the high stresses and strains near a notch result in a local annex to the reservoir of elastic potential energy. This means that there is a concentration of the energy

resulting from normal loading of the structure, at the area of the notch. This concentration of energy is available locally to promote crack initiation and propagation.

Thus there are three major causes contributing to rupture of metals; load, brittleness, and notches. They need not occur in the same amounts each time but will always be present in some degree when rupture occurs; and when an adverse combination of notches and brittle metal exists the structure may not be able to withstand the loadings of normal service.

From the above it is clear that a critical balance between available or potential energy and energy absorption capacity precedes each case of rupture. Thus the jeopardy of rupture can be reduced in either of two ways, i. e. by decreasing the potential energy locally or by increasing the ability of the structure to absorb energy.

The three approaches to reducing the jeopardy to the structure correspond to the three causes contributing to rupture:

1. Easing the loading
2. Using tougher metal
3. Easing the notches

There are now new possibilities for employing the first and last approaches, i. e. easing the loading or easing the notches. In recent tests steel bars with notches were loaded so that straining took place at a temperature above the ductile brittle transition zone. The same notched bars tested at temperatures below the ductile brittle transition temperature absorbed more energy than did bars which had not been prestrained at the higher temperature. Two hypotheses have been advanced to explain this behavior. The first hypothesis proposes that the crystals of the metal are re-oriented in the zone about the notch due to plastic flow under favorable warm temperature conditions. The second hypothesis is related to the first but goes another step with the proposal that the plastic flow results in compressive locked-in stresses at the apexes of the notches. As a result less potential energy is available locally to initiate fracture.

In connection with the second hypothesis a mathematical theory has been developed which defines the conditions required for a rupture to occur in metal of known rupture characteristics and in the presence of a notch. This theory shows that very high energy is required locally to start the crack. However, the converse is true also; the theory shows that minor reductions in internal stress level near a notch result in a major reduction in the chance of rupture.

In order to reduce the danger of rupture occurring in a metal structure two steps are needed. First, the metal must be heated so that plastic flow occurs easily, especially near notches. Second, the metal must be strained to promote the plastic flow. In this manner the new discoveries and theories can be put to practical use.

It is accordingly, an object of the present invention to provide a method for treatment of notched metal structures to reduce the possibility of ruptures.

It is a further object of the invention to provide a method of treating notched metal structures to increase their toughness to prevent failure of such structures in service.

It is a still further object of the invention to increase the toughness of fabricated metal structures involving a notch, especially during service of the structures below a certain critical temperature of the metal.

Other objects and many of the attendant advantages of this invention will be readily appreciated as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings wherein:

Fig. 1 is an explanatory diagram which shows one

manner of carrying out the method of the invention on a typical structure;

Fig. 2 is a schematic view of an apparatus utilizable in carrying out the method diagrammatically illustrated in Fig. 1;

Fig. 3 is a simplified view of apparatus adapted to practice the method in connection with structures;

Fig. 4 is a simplified vertical view, partly in section, showing another type of structure to which the method of the invention may be applied and apparatus which may be used to practice the method on this type of structure;

Fig. 5 is a view of a steel tensile type test specimen, drawn substantially to scale, to which the method has been applied; and

Fig. 5*a* is a front view of the specimen of Fig. 5, also drawn substantially to scale.

The method according to the invention involves the application of heat to the portion of a structure containing a notch, or suspected of containing a notch, as in the case of a weld as described above. The structure is warmed by a source of heat such as electricity, a gas flame, steam or other sources. No maximum temperature is specified but the metal should be warmed above its brittle-to-ductile transition zone whenever such a transition zone exists. Such transition zone temperatures for typical steels are set forth in the following Table 1:

TABLE 1

Temperatures during prestraining and tests

Steel Code	Brittle-to-Ductile Transition Temperature, Degrees F.	Prestraining Temperature, Degrees F.
A	130	180
B	90	140
C	87	140
D	180	240

The second column of Table 1 gives the mid-point of the brittle-to-ductile transition temperature zones of four structural steels. The third column of Table 1 gives a prestraining temperature used in increasing the toughness of notched steel specimens identical to those employed for determining the transition temperatures in column 1. The steel specimens employed to obtain the results in Table 1 is shown in Fig. 5 and Fig. 5*a*. A steel bar 55 was notched at **56** on each edge by a means of a hack saw. The tests were performed by pulling the specimen in direction indicated by arrows **57**. It is to be noted that the prestraining temperatures of Table 1 are approximately 50° F. above the mid-point of the transition zone. Higher prestraining temperatures probably would be more effective. Lower prestraining temperatures are not practical because; first, the brittle-to-ductile transition is a zone which could extend as much as 30° F. above the mid-zone temperatures listed in column 2 of the Table 1, and second, there are inaccuracies in temperature measurement so that lower prestrain temperatures could come dangerously close to the transition zone.

The notched tensile test speciment of Fig. 5 and Fig. 5*a*, employed to obtain the data of Table 1, is considered to be in an exceptionally bad notched condition. In fact the notched bar of Fig. 5 and Fig. 5*a* was found to produce brittle type fractures at a higher temperature than bad ship structural design details when the latter were manufactured from the same heat of steel and tested in full scale. In addition the structural steel D is about the most brittle, currently supplied in the structural grade. Therefore prestraining temperatures of not less than 240° F. will be effective for steel structures unless uncommonly extreme conditions of notching or brittleness are suspected to exist.

The steels A, B, C, and D of Table 1 conformed to the current American Bureau of Shipping and Navy Grade M specifications for ship hull steel. Their chemical analyses are tabulated in Table 2. However, it should be noted that chemistry alone does not determine brittleness of steel. Steels C and D were made specifically to represent extremes of toughness and brittleness respectively within the structural class for ship hulls.

TABLE 2

Chemical analysis of mill heats in percent

Steel Code	C	Mn	Si	P	S	Cu	N	Type of Steel [1]	Grain Size [2]
A	.18	.61	.055	.007	.021	.05	.0052	S-K	1-4
B	.17	.61	.054	.007	.020	.05	.0046	S-K [3]	5-8
C	.22	.55	.21	.013	.024	.22	.004	Si-K	--------
D	.20	.33	.01	.013	.020	.18	.002	Rim	--------

[1] Rimmed (Rim.), Semi-Killed (S-K), or Si-Killed (Si-K).
[2] McQuaid-Ehn.
[3] The steel for these plates was modified by the addition of aluminum in the ingot mold.

After and while the notched metal is warmed to above the brittle-to-ductile transition temperature zone, the metal is strained by some means of loading. The maximum amount of straining is not specific but it must be sufficient so that the metal strains plastically at dangerous notches. The direction of the straining should be generally the same direction as the direction of the principal tensile stress or stresses anticipated from loading in service. A typical example of the degree of preloading applied to steel to secure the desired plastic flow is a longitudinal tensile loading that causes the specimen of Figs. 5 and 5*a* which is twelve inches (12″) long, one inch (1″) wide and three quarters inch (¾″) thick to suffer a 0.005-inch reduction in thickness at point **58** midway between the notches **56**.

Straining of structures presumed to have notches may be accomplished by mechanical loading means, the thermal differential applying means, magnetic means or other force applying or loading means.

Straining by thermal differential means usually involves differential heating. The following specific example is described in conjunction with Figs. 1, 2 and 3 of the drawings.

Referring first to Fig. 1, a metal structure to be treated in accordance with the invention is designated at **11**. This structure has a notch or a presumed notch at a point or area indicated by the arrowhead **12**. A large area indicated at **13** surrounding the notch **12** is warmed so that the metal at the notch **12** is well above the brittle-to-ductile transition zone. Next strips represented by the narrow rectangular areas **14**, on opposite sides of the notch **12**, are cooled by some means such as cool air, water, solid carbon dioxide or other means. The area surrounding the notch **12** in the center portion of the area **13** is kept warm however. The shrinkage of the metal resulting from cooling of the areas **14** will contract the metal along an axis **16—16** parallel to the direction of the tensile stress anticipated in service, causing forces to be exerted as indicated by arrows **15** and causing the warm center zone surrounding the notch to stretch in the desired manner. The metal surrounding the notch is thus subjected to a plastic flow due to the thermally-created force exerted thereon.

The method described with respect to Fig. 1 may be carried out by the apparatus shown in schematic fashion in Fig. 2.

A structure **21** made up of plates **19** and **20** and containing a notch or presumed notch such as a weld **22** is to be treated by the thermal differential method generally described above. Gas burners or headers **26** serve to warm the structure **21** initially over an area similar to that described in the explanation of Fig. 1. The conduits **27** spray cooling water on the surface of the warm

structure over areas corresponding to areas **14** of Fig. 1. The result is to place a warmed area of weld **22** under a transverse tension in the manner described in connection with Fig. 1. The apparatus of Fig. 2 may be moved along the weld in the direction of arrow **23** to treat the weld containing the supposed notch along its entire length.

Fig. 3 shows a practical embodiment of the schematic arrangement of Fig. 2. The gas headers **26** and cooling water conduits **27** are mounted on a carriage in the same relative positions they occupy in Fig. 2. The gas headers **26** and conduits **27** are connected respectively to supplies of fuel and cooling water not shown. The carriage made up of a frame **28** and wheels **29** may be moved along the structure **21** at a rate determined by the material and size of the structure, the intensity of the flames, the temperature of the cooling fluid and other factors, in order to secure the proper amount of heating and cooling necessary to accomplish the results described above.

A variation of the method may be practiced on structures such as a compartmented oil tank ship shown in Fig. 4.

An oil tank ship **30** shown in section, has a hull **31** divided into compartments **40, 41, 42, 43, 44** and **45** by bulkheads **46, 47, 48, 49** and **50** as shown. The hull contains or is suspected to contain notches shown at **32** which are to be treated according to the method of the invention. Compartment **42** containing the suspected notches is filled with water ballast or cargo such as fuel oil to the level **37**. Conventional cargo heaters **36** common in tankers are now used to warm the ballast or fuel in compartment **42** and hence the suspected seam above the brittle-to-ductile transition temperature of the metal composing the hull **31**. Next the tanks **41** and **43** are filled to level **38**. The unequal ballasting of the compartments of the tanker will cause the notch **32** to be placed under tension by the unequal distribution of weight and buoyant forces over the ship structure. The material surrounding the notch is thus mechanically stressed in tension after having been heated and held above the critical brittle-to-ductile transition temperature zone.

The process might also be accomplished by applying fixed loads to other notched structures. Fixed loading could be applied, for example, to a truck frame containing notches. The particular means used to apply either heat or load to the structure is obviously not critical. Stresses may be applied by the thermal differential method, by mechanical loading or by a combination of these means. The structure is then allowed to cool, and may be placed in service with increased toughness.

It has been determined that the practice of the above method results in an increase in toughness of a notched structure, at temperatures below the brittle-to-ductile transition zone of the structure. This reduces the possibility of ruptures in notched structures under load within this lower temperature range.

The method may be applied on either old or new fabricated structures and on different types of metals. The principles underlying these methods indicate that they may be effective on welded, brazed, cast or forged structures or on structures fabricated by other means.

Obviously many modifications and variations of the present invention are possible in the light of the above teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed is:

1. A method for increasing the toughness of a notched metal structure, the structure comprising steel which has a notch brittle-to-ductile transition characteristic in a temperature range comprising ambient temperatures to which the structure will be subjected during service after performance of the method, the method comprising warming notched portions of the steel to a temperature above the notch brittle-to-ductile transition temperature range but at which plastic flow occurs readily, the last said temperature being significantly below the annealing range of the steel, and straining the portions while so warmed to promote plastic flow.

2. A method for increasing the toughness of a notched metal structure, the structure comprising steel which has a notch brittle-to-ductile transition characteristic in a temperature range comprising ambient temperatures to which the structure will be subjected during service after the performance of the method, the method comprising warming notched portions of the steel to a temperature in the order of 50° F. above the midpoint of the notch brittle-to-ductile transition temperature range, but at which plastic flow occurs readily, and straining the notched portions while so warmed in the general direction of the principal tensile stress anticipated therein in said service.

3. A method for increasing the toughness of notched portions of a ship, the portions comprising steel which has a notch brittle-to-ductile transition characteristic in a temperature range including ambient temperature to which the portions will be subjected after performance of the method, the method comprising warming notched portions of the steel to a temperature of at least approximately 50° F. above a central point of the notch brittle-to-ductile transition temperature range, but at which plastic flow occurs readily, the last said temperature being significantly below the annealing range of the steel, and stretching the warmed portions to promote plastic flow at the notches.

4. A method for increasing the toughness of a structure having a notched portion of steel which has a notch brittle-to-ductile transition characteristic in a temperature range including ambient temperature to which the portion will be subjected after performance of the method, the method comprising warming the notched portion of the steel to a temperature above the notch brittle-to-ductile transition temperature range, but at which plastic flow occurs readily, the last said temperature being considerably below the annealing range of the steel, and straining the steel for plastic flow in the general direction of the principal tensile stresses anticipated in said service.

5. A method for increasing the toughness of notched portions of a ship, the portions comprising steel which has a notch brittle-to-ductile transition characteristic in a temperature range including anticipated ambient temperatures to which the portions will be subjected after performance of the method, the method comprising warming notched portions of the steel to a first temperature above the notch brittle-to-ductile transition range, but significantly below the annealing temperature of said steel, but at which plastic flow occurs readily, and temperature treating metal adjacent said warmed notched portions to a temperature different from said first temperature, whereby to produce a thermal difference for straining the notches and causing plastic flow in the direction of the principal tensile stresses anticipated in service.

6. A method for increasing the toughness of a metal structure, the structure comprising notched portions of steel which has a notch brittle-to-ductile transition characteristic in a temperature range including ambient temperatures to which the structure will be subjected after performance of the method, the method comprising warming notched portions of the steel to a temperature above the notched brittle-to-ductile transition temperature range, but at which plastic flow occurs readily, the last said temperature being significantly below the annealing temperature range of the steel, and mechanically stretching the warm notched portions, whereby to induce plastic flow at the notches.

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