

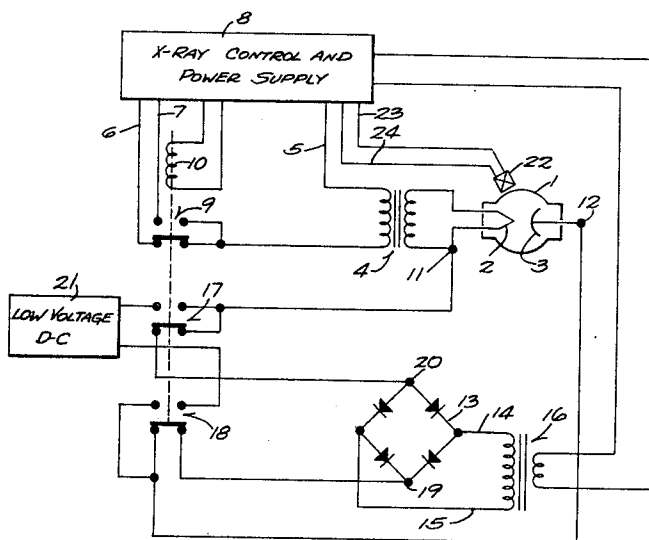
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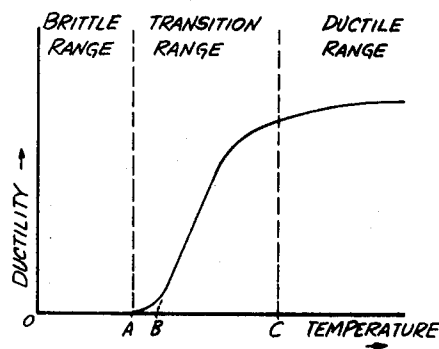
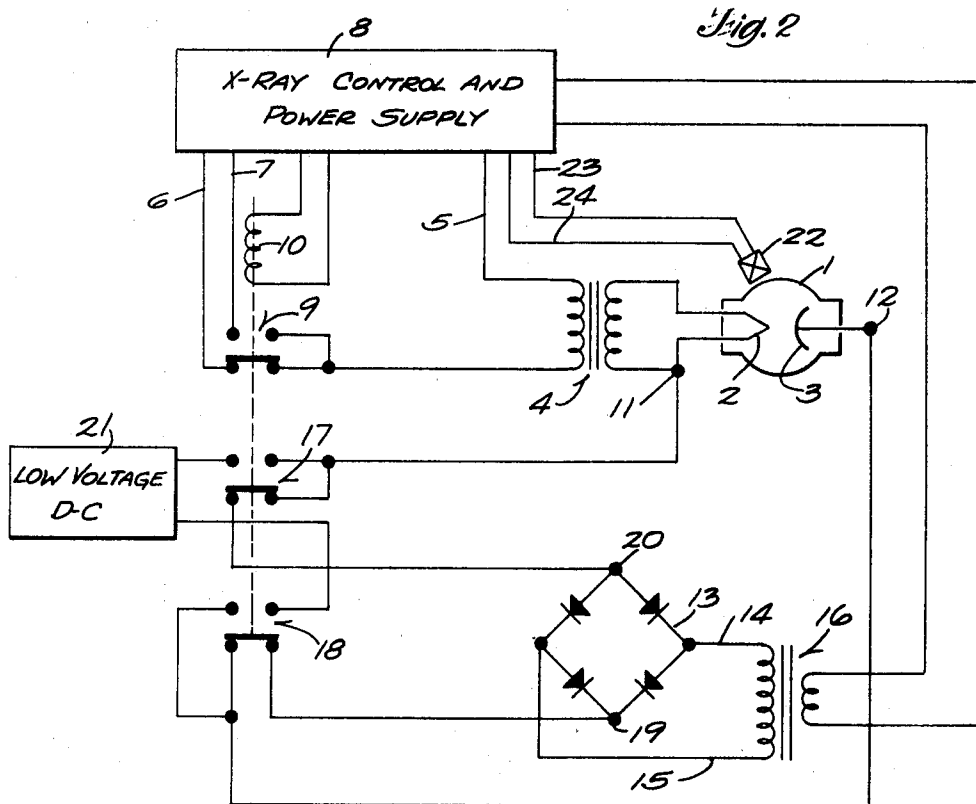
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[54] **METHOD AND APPARATUS FOR MITIGATING
 SURFACE DISRUPTION OF X-RAY TUBE
 TARGETS**
 4 Claims, 2 Drawing Figs.

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 [51] Int. Cl. **H01g 1/32**
 [50] Field of Search 250/93, 99,
 103

ABSTRACT: An x-ray tube target is heated to a temperature at which it is essentially ductile by directing a medium energy electron beam on it prior to and between normal high energy x-ray exposures. This permits the target surface to undergo plastic deformation rather than brittle fracture when it is subjected to the high mechanical stress caused by the large thermal gradients incidental to an exposure. Thus, target surface disruption is mitigated.





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METHOD AND APPARATUS FOR MITIGATING SURFACE DISRUPTION OF X-RAY TUBE TARGETS

BACKGROUND OF THE INVENTION

Operational life of an x-ray tube is most frequently terminated by its target surface becoming roughened and disrupted in the focal track region. This damage is caused by high thermal gradients and accompanying high mechanical stresses that occur in the target's surface layer when the target is cyclically heated and cooled by application and removal of an intense electron beam in connection with making x-ray exposures. The mechanical stresses initiate and eventually propagate brittle intragranular and intergranular fractures in the target material. The process is cumulative and sometimes leads to complete fracture of targets.

Disruption of the target surface results in a marked decrease in the useful radiation from the tube because the probability of an x-ray photon escaping from the target is less for a rough surface than for a smooth surface. Moreover, operators of x-ray apparatus tend to compensate for decreased radiation output by increasing the power level of the electron beam. High power densities cause still higher thermal gradients that create greater mechanical stresses which in turn cause more fractures to initiate and propagate in the surface of the target. This cyclic process leads to rapid failure of the tube.

Metallurgists have attempted to solve the surface fracturing problem in high temperature application of metals by a variety of means including increasing the purity of the metal, decreasing the grain size, redistributing impurities, controlling grain orientation, cold working and alloying. All of these techniques tend to lower the nil ductility temperature (NDT) above which metals are increasingly ductile and below which they are brittle.

NDT and other terms used in this specification will now be defined in reference to FIG. 1. This FIG. shows a typical plot of ductility versus temperature of a metal. Below temperature A the metal is brittle; this temperature region is called the brittle range. Above temperature C the metal is quite ductile; this temperature region is called the ductile range. Between temperatures A and C there is a region in which the ductility of the metal increases rapidly; this temperature region is called the transition range.

Plots of ductility versus temperature are generally S-shaped with an almost linear, high positive slope portion in the transition range. Nil ductility temperature (NDT) can be defined as that temperature at which a linear extrapolation of the linear, high slope portion of the ductility-temperature curve intersects the temperature axis at the point which is marked B.

The position of the curve with respect to the temperature axis and the slope of the linear portion depends on several factors such as the type of metal, its degree of cold work, its impurity content, the rate at which stress is applied during testing and others. Ductility may be expressed in several ways. In the curve shown, ductility may be considered as being expressed in terms of percent reduction in cross-sectional area at the fracture interface when a test piece is subjected to tensile stress and elongated until fracture occurs. Greater ductility is then indicated by greater reduction of area. Ductility may be expressed in terms of bending angle if a bending test is used.

If the shape of the curve is different because of one or more of the factors mentioned in the preceding paragraph, the NDT or point B would shift along the temperature axis, but would nevertheless, be a rather definite temperature regardless of the magnitude of the curve.

When a metal is ductile and is subjected to stress causing thermal gradients at its surface, the stresses are relieved by plastic deformation rather than by brittle fracture. When the metal deforms plastically, the stresses are relieved before brittle fracture can occur. In general, the tendency for brittle fracture is reduced by lowering the NDT of a metal, because the metal exists in a brittle state for a shorter period during a given thermal cycle.

The surfaces of x-ray tube targets are usually made of high atomic weight refractory metals such as molybdenum and tungsten. These metals are particularly susceptible to brittle fracture because they have relatively high NDT's and broad transition ranges as conventionally processed. Moreover, in the course of normal usage, the grain structure of a tungsten x-ray tube target may be subject to grain growth, thereby increasing the NDT even further.

SUMMARY OF THE INVENTION

An object of the present invention is to mitigate surface disruption of x-ray tube targets and thereby maintain their output of x-radiation at a relatively constant level. This object is achieved by providing x-ray apparatus with means for maintaining the steady-state temperature of the target at a predetermined level at least above the NDT of the target material during periods of rapid heating or cooling of the target surface layer. In this way, the target surface is maintained in a more ductile state during periods of high mechanical stress resulting from differential thermal expansion in the target. Ductility of the target surface region insures that it will react to stress by plastic deformation rather than by brittle fracture. The prevention of brittle fracture greatly reduces disruption of the target surface.

According to a preferred embodiment of the invention, the steady-state temperature of the target is maintained above its NDT and preferably fairly high in the transition range by heating the target with an electron beam of medium energy before and after high energy x-ray exposures are made. A preferred approach is to utilize an existing filament in the x-ray tube as the source of the medium energy electrons for auxiliary heating. In this approach, the x-ray apparatus is provided with a separate low voltage source that can be connected to the x-ray tube by means of an automatic switch when no exposure is being made. At the same time, the x-ray tube filament current is automatically adjusted so that the total power density of the electron beam is small as compared with the power density during sustained radiographic exposures. This heating power, usually in the target of 100 to 300 watts, is sufficient to maintain the temperature of targets made of any of the tube the common refractory metals stress their NDT. When a normal x-ray exposure is initiated, the auxiliary heating is discontinued and is not restarted until the target temperature falls to a predetermined level after some of the excess heat that usually results from an exposure is dissipated.

An additional object and benefit of maintaining the target above its NDT is that the tube is kept warm at all times. This facilitates distribution of electric charge within the tube and relieves the electrostatic stress when high voltage is applied in which case the likelihood of puncturing the glass envelope of the tube is reduced.

Another object and benefit of keeping the target warm is that the bearing structures of rotating anode tubes are subjected to less severe temperature variations than is the case with a cold tube when an ordinary high energy exposure is initiated. As a result, the bearings of the tube run more quietly and with less vibration.

How the foregoing and other more specific objects are achieved will become evident in the ensuing specification which describes a preferred embodiment of the invention in reference to the drawing.

DESCRIPTION OF THE DRAWING

FIG. 1 is a plot of ductility versus temperature for a representative metal; and

FIG. 2 is a schematic representation of the principal components of a conventional x-ray tube power supply circuit in which the invention has been incorporated.

DESCRIPTION OF A PREFERRED EMBODIMENT

In FIG. 2 a conventional rotating target x-ray tube is designated by the reference numeral 1. The tube includes a

directly heated cathode or filament 2 in spaced relationship with a rotating anode or target 3. Most tubes have several cathodes which are used alternatively for radiography and fluoroscopy, and for the purposes of the invention, an additional cathode may be used. All or some of the cathodes may be indirectly heated. The one filament shown in the tube of this example is heated by current from the secondary winding of a filament transformer 4. The primary of transformer 4 is energized through a common line 5 on one side of the primary and alternative lines 6 and 7 on the other side. Different voltages are applied to transformer 4 from an x-ray tube current control, not shown, which is conventional and is included in the x-ray control and power supply device 8. The filaments 2 or cathodes are usually energized with low voltage to keep them at standby temperature when the x-ray apparatus is turned on and they are automatically switched to higher voltages and full electron emissivity just before an exposure is made. Such last-mentioned switching means are not shown.

Lines 6 and 7 include two sets of relay contacts which are designated generally by the reference numeral 9. When a normal x-ray exposure is being made, one contact is closed as shown, in order to cause filament 2 to heat to a certain comparatively high temperature and emit electrons that are focused and impinged on target 3 to generate x-rays. The electron beam current from filament 2 to target 3 may range from a few milliamperes of long duration when making a fluoroscopic study to a thousand or more milliamperes for a fraction of a second when making a radiograph.

Contact 9 is operated by a coil 10 which closes the normally open contact in series with line 7 automatically prior to and between x-ray exposures. When this happens, a comparatively lower voltage is applied to filament transformer 4 and there is a corresponding reduction of filament temperature which results in low electron beam current through the x-ray tube 1.

High voltage is applied across the filament terminal 11 and the anode terminal 12 of the x-ray tube from a full wave bridge rectifier 13. The AC input lines 14 and 15 for rectifier 13 extend from the secondary winding of a high voltage x-ray transformer 16. The voltage supplied to the primary of transformer 16 is adjustable at the will of the operator by such means as, for example, selecting autotransformer taps, not shown, in the x-ray control and power supply 8. The number of primary voltage steps available are usually such that high voltages ranging from about 30 peak kilovolts to 150 peak kilovolts can be produced on the secondary of transformer 16.

Relays 17 and 18 are in the high voltage circuit. The lower contacts of each relay are shown closed as they would be during a normal x-ray exposure. During an exposure, a circuit is completed from DC terminal 19 of rectifier 13 through closed contact 18, to x-ray tube 1, and through closed contact 17 and back to the other DC rectifier terminal 20.

Before and after an x-ray exposure, the contacts of contactors 17 and 18 are transferred by operation of relay 10 to close their respective pairs of contacts and connects a low voltage DC power source 21 across terminals 11 and 12 of the x-ray tube. Tracing the circuit will demonstrate that the low voltage DC source 21 is isolated from the high voltage supply described above when contactors 17 and 18 are transferred.

The low voltage DC source 21 is preferably limited to 10 kilovolts peak voltage. Some low intensity x-radiation will be generated in x-ray tube 1 when the low voltage from source 21 is applied to the tube, but this soft radiation can be absorbed by the x-ray tube envelope. Of course, the absorption by tubes of different manufactures will vary so it is desirable to run carefully controlled tests to determine the maximum voltage that can be applied without causing excessive x-ray output. The low voltage supply should be designed so that it cannot be adjusted to a voltage that will cause an undesired amount of x-ray output.

A temperature sensing device 22, which may be a semiconductor, is placed near the x-ray tube 1 in order to sense the temperature of the x-ray tube target 3 optically. This device

22 is connected to the x-ray control 8 by conductors 23 and 24. The function of device 22 and the logic circuitry, not shown, in which it is incorporated is to turn on auxiliary heating or preheating if the target 3 is below its NDT or other predetermined temperature in the transition range, and to turn it off if the target exceeds the predetermined temperature from heat due to auxiliary heating or to making an exposure.

Whenever the x-ray apparatus is turned on in expectation of making high energy x-ray exposures, according to the invention, it is necessary to elevate the temperature of target 3 to at least above its NDT and preferably high in the transition range before an exposure is made. For this reason, the x-ray control is interlocked so that relay coil 10 is energized when power comes on. This causes all the contacts which are shown open in the drawing to close in which case low voltage from source 21 and low electron beam current are applied to the x-ray tube to heat the target and bring it up to at least above its NDT. For the heaviest targets that are now in use, it has been found that about 5 minutes are required for initially preheating the target to a satisfactory level.

When a normal x-ray exposure is initiated, relay coil 10 is deenergized and the contacts in contactors 9, 17, and 18 are transferred to the position in which they are shown, in which case the voltage and current through the x-ray tube 1 are subject to the control of the conventional current and voltage control device which are found in the x-ray control and power supply 8.

At the termination of each normal x-ray exposure or sequence of exposures, the temperature of the target 3 as determined by temperature sensor 22 is compared to the desired steady-state target temperature T, which is a temperature in the ductile range of the particular tube target. If the target temperature is above T, relay 10 is not reenergized and normal target cooling proceeds until the target temperature falls below T at which time relay 10 is reenergized. If at the termination of the x-ray exposures, the target temperature is below T, relay 10 is energized and electron bombardment heating of the target 3 resumes. The T that is chosen will usually be nearer to temperature C in the transition range of FIG. 1 than to temperature B so that the target will be near its highly ductile state when subjected to normal exposure loading.

The target temperature sensor 22 and its associated circuitry to control 8 act to maintain the target 3 at a temperature as close to T as possible. If T is exceeded either during auxiliary heating or during normal x-ray exposures, relay 10 is deenergized and the power from low voltage supply 21 is prevented from reaching tube 1. Alternatively, if the target temperature falls below T, relay 10 is energized, permitting power from supply 21 to reach the tube.

The wattage required for maintaining x-ray tube target 3 above its NDT and in or slightly above its transition temperature range depends on a number of factors including the heat dissipation of the tube, the mass of the target, and the type of material out of which the target is made. Molybdenum targets may have an NDT below 100° C. Tungsten targets may have an NDT ranging from 200° to greater than 600° C., depending on their structure and metallurgical history. It is desirable not to exceed the transition temperature range of a particular material by an undue margin of safety because some of the thermal capacity of the tube is utilized by auxiliary heating or preheating the target. Although the specific NDT of any target material should be ascertained, a general idea may be obtained by referring to the plots of temperature versus ductility which are shown in several publications including "Refractory Metals and Alloys," Vol. 2, Interscience Publishers, 1963.

Commercial embodiments of the invention use 300 watts of auxiliary heating power for x-ray tubes that have a massive tungsten target about 3 inches in diameter and nominally one-fourth to one-half inch thick. This heat is generated with a low voltage DC power supply 21 operating at 9 kilovolts peak and with the filament heat adjusted so that a little more than 20 milliamperes are conducted by the x-ray tube under standby

conditions. A low voltage DC power supply 21 which is adjustable between 2 and 10 kilovolts peak will be satisfactory for almost any rotating anode x-ray tube that is currently in use. 100 to 500 watts of power appears to offer a sufficiently broad range to handle almost any x-ray tube.

The preferred embodiment of the invention which was described above will now suggest to those skilled in the art other approaches to auxiliary heating of the target in order to maintain it above its NDT and in the transition range. For instance, it is possible to provide an additional low voltage step for the high voltage x-ray transformer 16 primary and to automatically switch to this step when a need for preheating is sensed before and after each x-ray exposure. Means can also be provided for switching the filament current to a lower level simultaneously as in the preferred embodiment. Another approach is to provide the x-ray tube with an additional hot cathode and focusing gun so that a preheating electron beam may be directed either at the front or at the back of the target, if desired, in which case the high and low energy supplies to the x-ray tube may be more completely isolated. In gas-filled tubes, ion bombardment may be the most practical way of heating. Electrical resistance heating, infrared heating, laser heating, radiofrequency and ultrasonic heating may also be used. In grid controlled x-ray tubes, a suitable control voltage may be applied to the grid between exposures in order to limit electron beam current in the tube during auxiliary heating. If it is desired to provide auxiliary heating with low electron beam currents and a voltage that is so high as to cause undue x-ray emission from the tube, an automatic shutter, not shown, may be provided over the x-ray tube exit window to provide sufficient shielding during the time intervals in which auxiliary heating is activated.

The benefits of preheating of x-ray tube targets are demonstrated by tests which have been conducted on groups of x-ray tubes that were as near to being identical as possible. One group was subjected to thousands of radiographic exposures without preheating. The other group was similarly operated but with preheating. Radiation output was measured at regular intervals throughout the tests. The number of exposures was plotted against radiation output. It was found that there is a gradual decline in radiation output for the tubes that were operated without preheating as the number of exposures increased. Almost all such tubes had reached the end of their useful life after several thousand exposures. Some failed much earlier. The tubes that were operated with auxiliary heating or preheating exhibited very little reduction in x-ray output for equal numbers of exposures and their surfaces were not disrupted. The useful life of the tubes was generally four times longer than those which were operated without preheating.

In summary, a simple and effective method of reducing x-ray tube target surface disruption has been described. It involves establishing the target at above its nil ductility temperature, at least, and preferably high in the transition range, before normal x-ray exposures are made. This selective auxiliary heating is achieved in the illustrative embodiment with electron heating by operating the x-ray tube at a relatively low power level before normal high power exposures are made. Other methods for providing auxiliary heating of the target are

suggested.

We claim:

1. X-ray apparatus that is adapted to mitigate brittle fracture of the target of an x-ray tube which is used in the apparatus by maintaining the target surface material above its nil ductility temperature prior to making an x-ray exposure, comprising:
 - a. terminals for receiving an x-ray tube therebetween and for applying a voltage between a cathode and a target of the tube;
 - b. an x-ray power supply adapted to selectively energize the tube for making an x-ray exposure an incident of which is the development of high thermal gradients and stresses in the target;
 - c. auxiliary means for heating said target to at least above its nil ductility temperature prior to making an exposure to thereby permit said stresses to be relieved by plastic deformation instead of brittle fracture when an exposure is made; and
 - d. means adapted to sense the temperature of the x-rays tube target and to control operation of said auxiliary heating means.
2. The invention set forth in claim 1 wherein:
 - a. said auxiliary heating means comprises a source of voltage; and
 - b. switch means, said switch means being operated in response to said target temperature sensing means and being adapted to selectively apply said voltage between the target terminal and a cathode terminal of an x-ray tube prior to an exposure.
3. The invention set forth in claim 2 wherein the peak voltage limit of said voltage source before an exposure is a voltage at which no significant x-radiation is emitted from the x-ray tube during auxiliary heating.
4. X-ray apparatus that is adapted to mitigate brittle fracture of the target of an x-ray tube which is used in the apparatus by maintaining the target surface material above its nil ductility temperature prior to making an x-ray exposure, comprising:
 - a. terminals for receiving an x-ray tube therebetween and for applying a voltage between a cathode and a target of the tube;
 - b. alternate sources of voltages, one voltage being applied across the terminals to generate x-rays for making an x-ray exposure, the other voltage being applied across the terminals primarily for raising the temperature of the x-ray target above a predetermined value which is at least above the nil ductility temperature;
 - c. a switch means adapted to connect alternatively one or the other of the voltage sources across the target and a cathode;
 - d. target temperature sensing means; and
 - e. means responsive to the target temperature sensing means to selectively operate said switch means to connect the other voltage source before an exposure is made if the x-ray tube target is below said predetermined temperature.