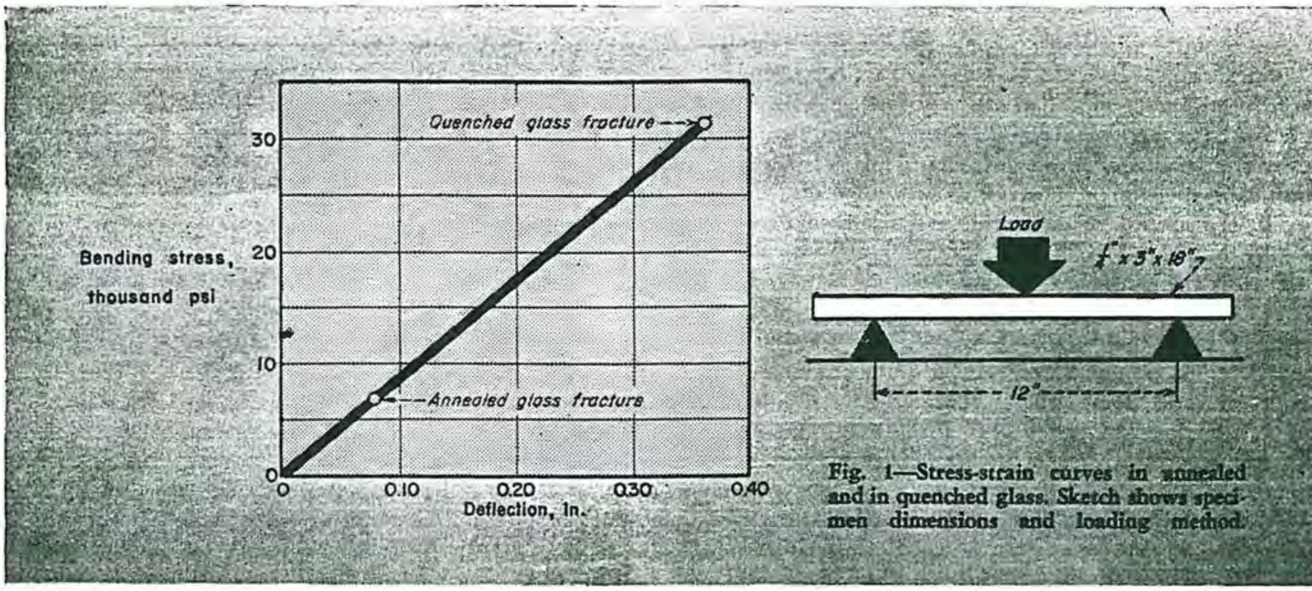

Fig. 1—Stress-strain curves in annealed and in quenched glass. Sketch shows specimen dimensions and loading method.

Residual Compressive Stress Strengthens Brittle Materials

Effect of retained residual compressive stress on the ductility of the surface layer of brittle materials in reducing applied surface tensile stress. Spring test data demonstrate the beneficial effect of residual compressive stress in the surface of hard steel.

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UNDER CONDITIONS of brittle fracture, specimen surfaces are weaker than sound subsurface material. When such relatively weak surfaces are residually stressed in compression, the specimens will support greater tensile loads and will exhibit greater ductility because the applied surface tensile stress is reduced by an amount equal to the retained residual compressive stress.

The strengthening effect of residual compressive stress in brittle materials is perhaps most easily demonstrated with glass specimens. Among the advantages of glass for evaluating residual stresses is that at ordinary temperatures glass is completely brittle. For this reason, the residual stress pattern remains unaltered by plastic flow to the instant of fracture. Also, any apparent unorthodox behavior of glass will not mistakenly be attributed to cold work or altered structure.

Residual compressive stress in glass surfaces is developed by rapid cooling, usually by air jets, from some elevated temperature at which glass is plastic. The surface of the glass in cooling contracts, thereby plastically deforming the still hot and ductile subsurface glass. As cooling continues, the subsurface glass contracts against the relatively cool and rigid surfaces, resulting in residual tensile stress in the core and corresponding residual compressive stress in the surface.

The relative static strength of a specimen of normal glass, which was carefully annealed to avoid residual stresses, and that of a similar glass specimen that had been quenched on both surfaces as described in the preceding paragraph is shown in Fig. 1. As shown by the insert in Fig. 1, these specimens were ordinary ¼ in. plate glass, 3 in. wide and 18 in. long. Each was placed on supports spaced 12 in. apart, then downward acting loads were applied at the mid-points. It is seen that the annealed glass failed at 7,000 psi calculated stress, and that the residually stressed glass did not fail until a calculated stress of 32,000 psi was reached.

Residual stress in quenched glass has been measured photoelastically by Littleton (Ref. 3). In Fig. 2 are shown the results of these measurements as applied to the specimens of Fig. 1. The surface residual compressive stress of the quenched specimen is seen to approximate 25,000 psi. In beam loading, the surfaces of the quenched specimen were nominally stressed to 32,000 psi. Since the actual or resultant stress is the algebraic sum of the residual stress and the nominal stress, the resultant stress ranges from

$$32{,}000 + 25{,}000 = 57{,}000 \text{ psi}$$

compression, as shown on the upper surface of the diagram Fig. 2, to

$$32{,}000 - 25{,}000 = 7{,}000 \text{ psi}$$

tension, as shown on the lower surface of the diagram Fig. 2, with a maximum subsurface tensile stress of 21,000 psi.

Thus it is seen that the quenched glass specimen failed at the same resultant tension surface stress as the annealed glass specimen, but the former supported a load four times as great as the latter. This increase in load carrying capacity was possible because brittle materials fail only by tension and subsurface tensile strength is greater than surface tensile strength.

The advantages of prestressed glass have been known and the quenching process has been commercially applied for upward of a century. Early applications were the strengthening of wine glasses and similar glassware. During the kerosene age, extra strong prestressed lamp chimneys commanded premium prices. Today almost every automobile uses quenched glass. Also, extensive use of such glass is seen in the numerous unframed glass doors used in stores and other commercial buildings.

Prestressed steel has also seen long and varied use in many machine parts that require extremely hard steel to resist wear, but in which brittleness must be avoided because the parts are also highly stressed, (Ref. 4). Such demands have been and continue to be met by processing to obtain hard surfaces and "tough" cores, that is, by case hardening. The hard case, whether obtained by carburizing, nitriding, or cyaniding, would be just as brittle as through hardened steel of the same hardness except for the fact that, when properly applied, the hard cases resulting from these processes are, like quenched glass, residually stressed in compression. Incidentally, the core in such specimens is "tough" only because, being submerged, it is not afflicted with surface weakness.

Shot peening, which produces residual compressive stress in the peened surfaces, is more effective in reducing brittle fractures when applied to hard brittle steel than to soft ductile steel because surface vulnerability increases as ductility decreases. The beneficial effect of residual compressive stress in the surface of hard steel is shown in Fig. 3. In these charts, the bars show the relative fatigue durability of three groups of coil springs that differ only in hardness and prestressing treatments.

The lower chart shows a summary of the fatigue durability of thirty-two production springs in terms of their average life, which was 157,000 cycles, when subjected to repeated compressive loads. The chart also shows their life variability, which ranged from a minimum of 45,000 cycles to a maximum of 355,000 cycles.

These springs had been heat-treated to Rockwell C52-53 hardness followed by preset, that is, the springs were compressed to solid height at 575 F. This operation caused plastic yielding in the most highly stressed regions, thereby reducing the maximum stress under subsequent loads. They were then shot peened at an intensity of 0.017A2 and again preset, this time at room temperature.

To measure the effect of high hardness on fatigue durability, four springs commercially identical with the thirty-two production springs were prepared as indicated in the upper bar charts of Fig. 3. These experimental springs were quenched from the same temperature and in the same medium as the production springs but the tempering treatment was omitted. Their hardness was Rockwell C61-63. Two of the four springs were then shot peened at an intensity of 0.026A2. This intensity was higher than that used in peening the production springs because the hardness of the metal to be peened was higher, and the peening treatment preceded presetting because of the possibility of damaging (Ref. 5) the hard unpeened steel by presetting. To avoid loss of hardness, the four springs were finally preset at 300 F instead of 575 F used on the production springs.

When fatigue tested under the same loads that were applied to the production springs, the non-peened hard springs failed in less than 10,000 cyles, whereas the minimum life of the shot peened hard springs exceeded the maximum life of the production springs. More significant, because of the small number of hard specimens tested, is their greater maximum life.

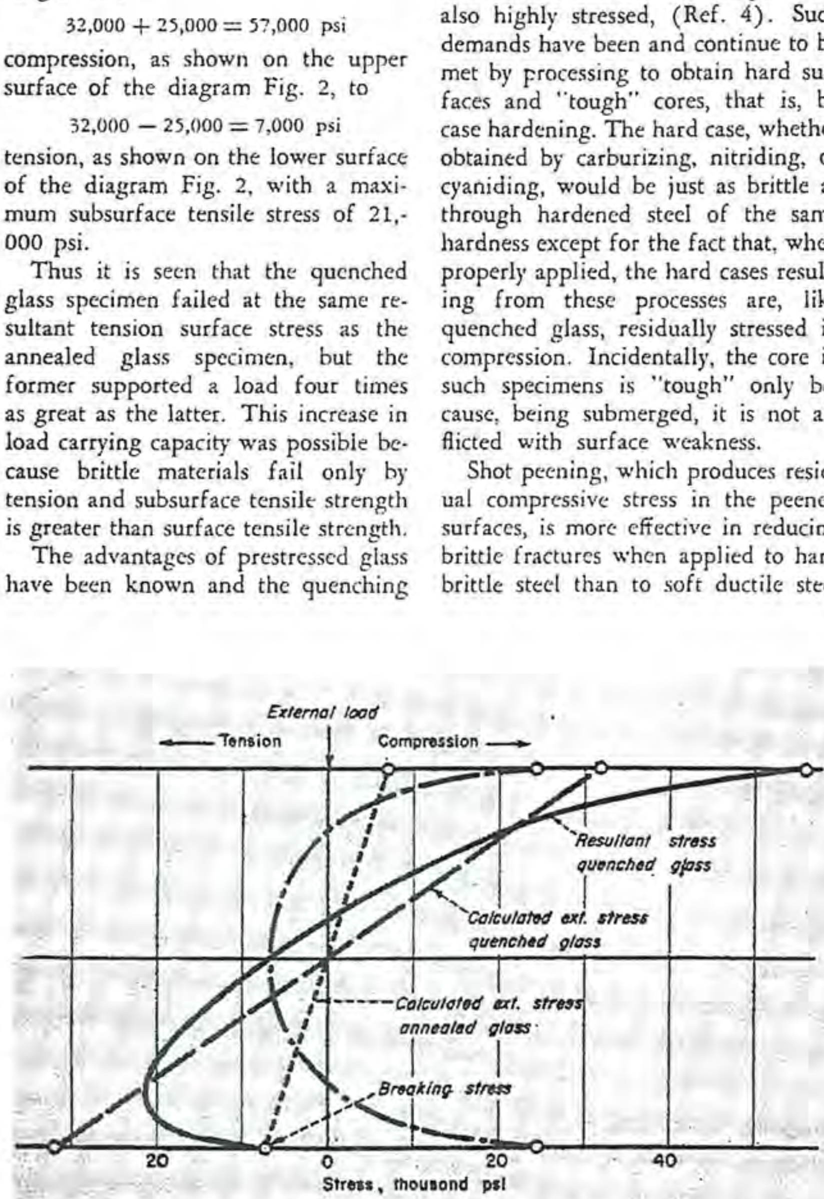

Fig. 2—Reconstructed diagrams to show stress distribution in glass beam specimens when they were loaded to failure.

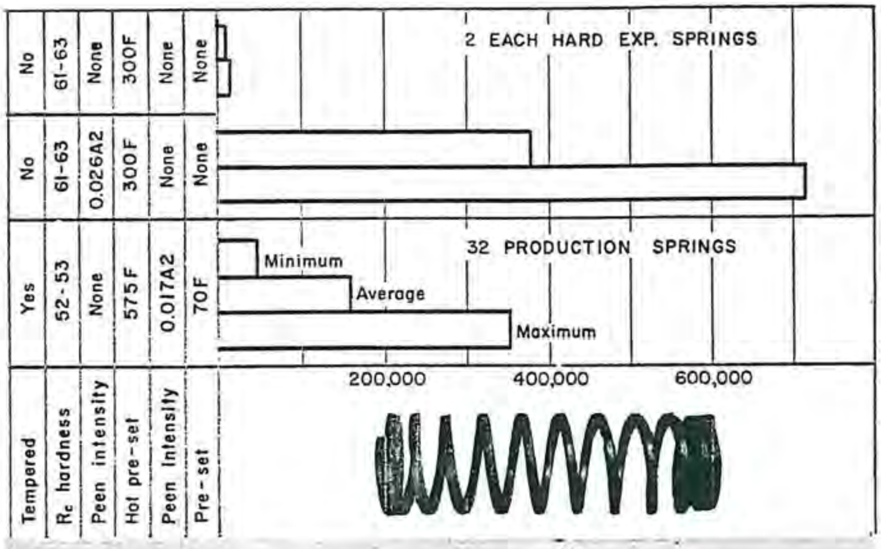

Fig. 3—Relative fatigue durability of groups of coil springs that differ only in hardness and prestressing treatments.

This increase in fatigue durability cannot be attributed to work hardening because the hardness of very hard steel is not increased by shot peening.

The greater intrinsic strength of the harder steel could not be realized in the non-peened springs because of surface weakness. But when the surface tensile stress was reduced by the residual compressive stress that was induced by peening, some of the greater subsurface strength became available. It is possible that had these hard springs been strain peened to increase the magnitude of the residual compressive stress (Ref. 2), even greater fatigue durability would have resulted.

The tests on these production and experimental springs were made during World War II by the Spring Division, Eaton Manufacturing Company, as part of a cooperative research program that included the Research Laboratories Division, General Motors Corporation.

Similar effects may be expected from any other process, including stretching, that protects the surface with a layer of compressively stressed metal. Conversely, processes that develop residual tensile stress in steel surfaces increase brittleness.

Several thermal and mechanical processes, other than those mentioned in the preceding paragraphs are known to induce residual compressive stresses in steel surfaces. Additional thermal processes are drastic quenching of low hardenability steel, steel quenched from tempering temperatures higher than 800 F, induction hardening, and flame hardening. Among additional mechanical processes are superficial rolling, honing, tumbling, several machining operations, and certain cold forming and straightening production operations.

Processes that increase brittleness by inducing residual tensile stress in steel surfaces are welding, flame cutting, grinding, and probably the opposite of stretching, that is, axial compressive loading sufficient to cause permanent deformation. Most of the currently used cold straightening and cold forming processes reduce brittle strength and ductility of steel because they induce residual tensile stress in the surface metal.

Because of the enhanced ductility and strength of potentially brittle metals processed to develop surface residual compressive stress, such treatments should be applied to all hard machine parts, especially when used at low temperatures. Since the damaging effects of surface residual tensile stress are increased at low temperatures, processes that induce such stresses should be avoided.

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