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The embrittlement of hardened, tempered low-alloy steel by strain aging

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SYNOPSIS
The susceptibility of a low-alloy steel that has been hardened and tempered—826 M40 (EN26)—to embrittlement by strain aging during service was simulated by artificial aging of specimens at 100°C. It was found that the brittle transition temperature of both monotonic and cyclically strained material was increased by only about 25°C as a result of strain aging. It is concluded that the susceptibility of low-alloy steels in the hardened, tempered condition is less than that of low-carbon steel, and that such steels qualify for exemption of the periodic 'annealing' required by the Mines and Works Act.

SAMEVATTING
Die vatbaarheid vir verbrossing deur rekveroudering van 826 M40 (EN26) 'n lae-legeringstaal gedurende gebruik is gesimuleer deur die kunsmatige veroudering van monsters by 100°C. Dit is bevind dat die verhoging in brosoorgangstemperatuur vir beide enkelvoudige en siklies-rekverouderde materiaal slegs in die omgewing van 25°C is. Daar word afgelei dat die vatbaarheid vir verbrossing van lae-legeringstaal in die verhard en getemperde toestand minder is as die van lae-koolstofstaal en dat sodanige lae-legeringstale behoort te kwalifiseer vir vrystelling van periodieke 'uitgloeïng', soos vereis deur die Wet op Myne en Bedrywe.

Introduction

When steel has been strained (deformed plastically) and then allowed to age, it has been subjected to what is known as strain aging. Fig. 1 shows the stress–strain curve for mild steel (low-carbon steel) compared with that for the same steel prestrained up to point B and then subjected to aging. As a result of the strain aging, the yield strength and the tensile strength were increased by ΔY and ΔU respectively, and the elongation was decreased by amount Δe.

In general, strain aging increases strength to some extent but results in a loss of some ductility. It is known that strain aging is accompanied by a decrease in fracture toughness, which is usually reflected by an increase in the brittle transition temperature (BTT).

Mechanism of Strain Aging

It is generally accepted[1] that strain aging is due to the diffusion of carbon and/or nitrogen atoms in solution to dislocations that have been generated by plastic deformation. Initially, an atmosphere of carbon and nitrogen atoms is formed along the length of a dislocation, immobilizing it. Extended aging, however, results in sufficient carbon and nitrogen atoms for precipitates to form all along the dislocation. These precipitates impede the motion of subsequent dislocations, and result in some hardening and loss in ductility. The extent of strain aging, which is a thermally activated process, depends primarily on aging time and temperature. In general, extended aging results in a saturation value above which further aging has no effect. In fact, aging at very high temperatures can result in over-aging, which is accompanied by a loss in hardness and a gain in ductility. Repeated straining and aging usually produce a greater increase in strain aging.

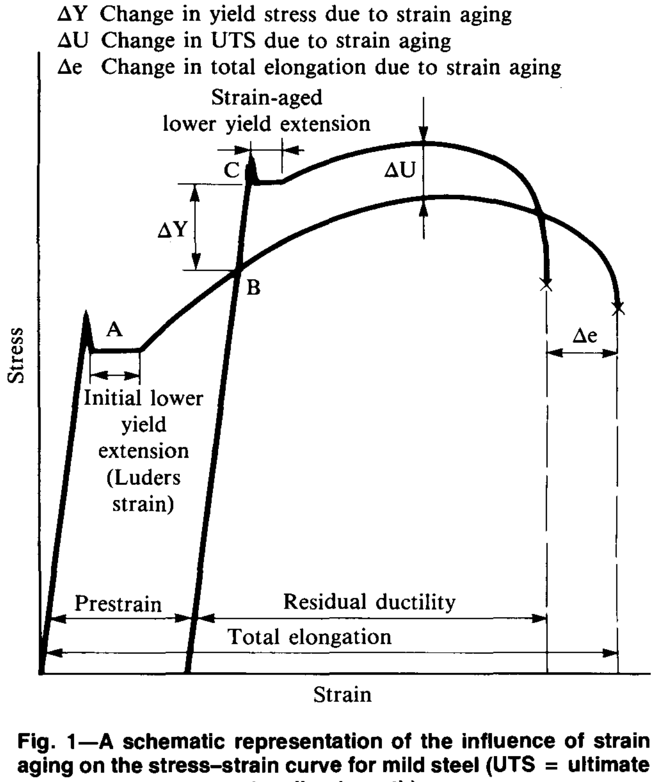

Fig. 1—A schematic representation of the influence of strain aging on the stress–strain curve for mild steel (UTS = ultimate tensile strength)

For strain aging to manifest itself, free carbon and nitrogen atoms in solid solution have to be available, but very little carbon and nitrogen are required. As little as 0,01 per cent, for example, is sufficient to produce

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substantial strain aging. Stabilized (non-aging) steels, which are less susceptible to strain aging, can be manufactured by the addition of alloying elements that have a very high affinity for carbon and nitrogen and in this way decrease the amount in solid solution available for strain aging. The principal element that is used for this purpose is aluminium, which forms aluminium nitride. Elements that are strong carbide formers, such as titanium and chromium, are also effective in reducing the amount of carbon in solid solution.

Strain-age Embrittlement

One of the unfortunate qualities associated with strain aging is a decrease in fracture toughness. This usually manifests itself by an increase in the BTT as determined by Charpy impact testing of notch samples at various temperatures. The increase in BTT is, in the first instance, due to the direct influence of plastic straining, which results in some strain hardening. Aging of the strained material, however, produces a further increase in BTT. In practice, this increase is not serious if the original BTT is low enough. As long as the BTT after strain aging is still substantially below the operating temperature[2] of the component, ductile behaviour is assured.

Any component that is subjected to plastic straining during use will be subject to strain aging during its subsequent use at room temperature. This is the reason why the Mines and Works Act requires periodic 'annealing' of critical components, of a hoist for example, to restore the impact properties. The extent to which the BTT is affected by strain aging is determined by the susceptibility of the steel to strain aging. For the present purpose, susceptibility to strain aging can best be judged by an increase in the yield stress, ΔY, brought about by aging (Fig. 1). The maximum value[3] of ΔY that can be expected in low-carbon structural steel after aging to saturation, is about 60 MPa. The actual extent of ΔY will depend, apart from aging conditions, on the chemical composition and metallurgical structure of the steel. The response to strain aging is usually a maximum in fine-grained steel of very low carbon content. As the percentage carbon content in the steel is increased, the susceptibility of the steel to strain aging is reduced. This applies particularly to hardened, tempered steel, which hardly shows the yield-point effect that is associated with strain aging. Fig. 2 shows the results of prestraining and subsequent aging on the Charpy impact energy of Bessemer steel.

The graphs show an increase in transition temperature of about 25°C for a prestrain of 10 per cent. Subsequent aging resulted in another 75°C increase in the BTT. This large increase in BTT of about 100°C applies to Bessemer steel and is due to the abnormally high nitrogen content of this type of steel, which is no longer manufactured. Increases in BTT of about 50°C as a result of strain aging[2,5] can be expected in the low-carbon structural steels that are manufactured at present. An exhaustive literature survey, including a Metadex Database computer search, to determine the extent to which the BTT of hardened, tempered low-alloy steels is affected by strain-age embrittlement, did not provide definite answers. The susceptibility of such steels had therefore to be determined experimentally with a view to obtaining exemption from

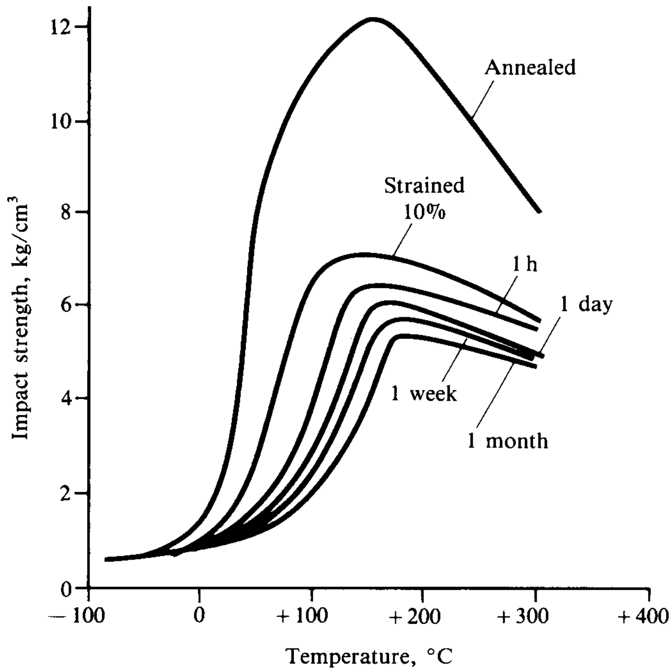

Fig. 2—The influence of straining and subsequent aging on the Charpy impact energy of a Bessemer steel (according to Von Kockritz[4])

the requirement of the Mines and Works Act for periodic 'annealing'.

Strain-aging Kinetics

Strain aging is a thermally activated process that requires the diffusion of carbon and nitrogen to form Cottrell atmospheres along dislocations. The aging kinetics are therefore influenced by both the temperature at which aging occurs and by the aging time. In general, the rate of aging is increased when the aging temperature is raised. The aging process can thus be accelerated artificially to simulate the aging that can be expected to occur naturally at ambient temperature during the life of a component.

The time (t) required for artificial aging at temperature T can be related to the period (t_r) for which the component will be subject to natural aging during its lifetime at an ambient temperature of T_r by the following two relationships for carbon and nitrogen aging:

$$\log \frac{t_r}{t} = 4400\left(\frac{1}{T_r} - \frac{1}{T}\right) - \log \frac{T}{T_r} \text{ (carbon aging)}$$

and

$$\log \frac{t_r}{t} = 4400\left(\frac{1}{T_r} - \frac{1}{T}\right) - \log \frac{T}{T_r} \text{ (nitrogen aging).}$$

A comparison of these two equations shows that nitrogen aging occurs at a slower rate than carbon aging. Table I shows the time required for artificial aging at

100°C to reach the same degree of aging as that of a component with an estimated life of 30 years at an ambient temperature of 30°C.

TABLE I

EQUIVALENT AGING TIMES AT TEMPERATURES OF 30°C AND 100°C

Process	Aging temperature	Aging time
Natural aging	30°C (303 K)	30 years (10 950 days)
Artificial aging:		
Carbon aging	100°C (373 K)	25 days
Nitrogen aging	100°C (373 K)	45 days

Experimental

For the purpose of the experimentation, a NiCrMo steel 826 M40 (EN26) was selected as representative of a high-strength low-alloy steel that is well known for its good response to heat treatment and for its high toughness and low BTT. The chemical composition of this type of steel is shown in Table II.

TABLE II

CHEMICAL COMPOSITION OF BS 970: 1972–826 M40 STEEL (IN PERCENTAGES)

Carbon	0,36/0,44
Manganese	0,45/0,70
Phosphorus	0,04 max.
Sulphur	0,04 max.
Silicon	0,10/0,35
Chromium	0,50/0,80
Nickel	2,30/2,80
Molybdenum	0,45/0,65

So that the specimens would be representative, they were machined from a shaft that had been hardened and tempered and was in the unaged condition. Specimens were machined in the axial direction. A metallographic examination of polished samples showed that the steel had an average non-metallic content. Fig. 3 shows the metallographic structure at low and high magnification.

At low magnification by use of the enhanced contrast with Nomarski interference microscopy, some residual bonding as a result of interdendritic segregation during solidification could be seen. The photographs of Fig. 3 are representative of properly hardened, well-tempered steel. The absence of detrimental primary ferrite and upper bainite in the structure is indicative of a quenching rate in excess of the critical rate.

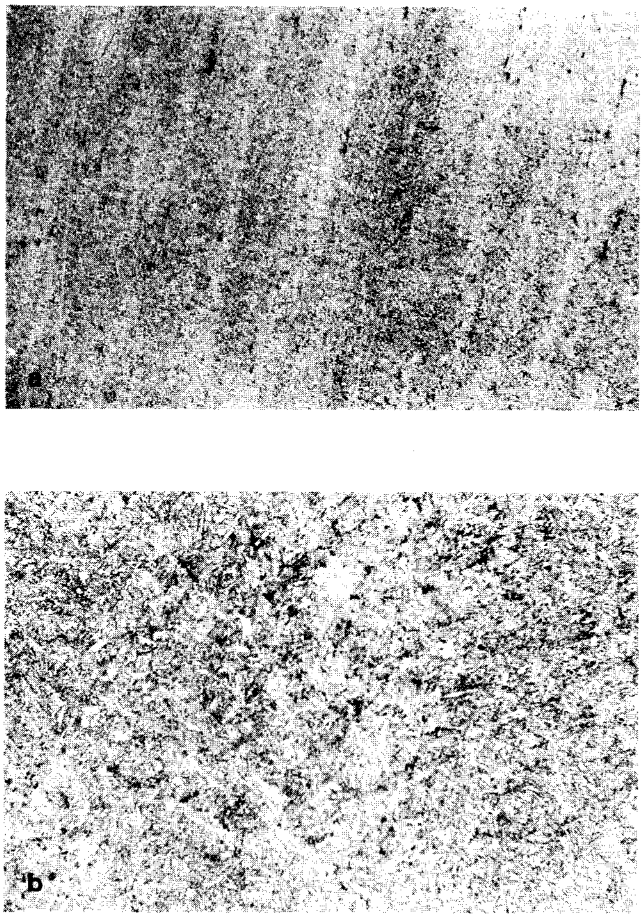

Fig. 3—The microstructure of a steel shaft at a magnification of (a) 55X and (b) 800X

Mechanical Properties

Fig. 4 shows an extensometer X–Y plot of the stress–strain curve of the material as received. The mechanical properties, shown in Table III, are quite acceptable and representative of sheave-wheel spindles made from 826 M40 steel.

TABLE III

MECHANICAL PROPERTIES

Property	B.S. 2722 grade 826 M40	Material
Yield strength (R_p), MPa	725 minimum	798
Tensile strength (R_m), MPa	930 minimum	960
Elongation (A), %	12 minimum	18
Red in area (Z), %		66
Vickers hardness, HV		295

Fig. 4 shows a very slight yield-point effect, which is due to the immobilization of dislocations by the Cottrell atmospheres formed. The susceptibility of the material to strain aging was determined by the usual straining followed by aging. For all the tests, the aging temperature was 100°C for a period of 50 days. As shown previously, this corresponds to the extent of natural aging that can be expected during a service period of 30 years at an ambient temperature of 30°C.

An X–Y plot with extended stress strain scales is shown in Fig. 5. The testing was interrupted after straining 1,5 per cent, after which the specimen was aged and tensile testing resumed. Fig. 5 shows a small amount of strain aging, which corresponds to an increase in yield strength (ΔY) of only 31 MPa. This corresponds to an increase in the yield stress of only 3,8 per cent.

So that the extent of strain aging could be assessed, oversize Charpy specimens were strained 2,5 per cent by compression and then aged for 50 days at 100°C. In another experiment, Charpy specimens were strained by

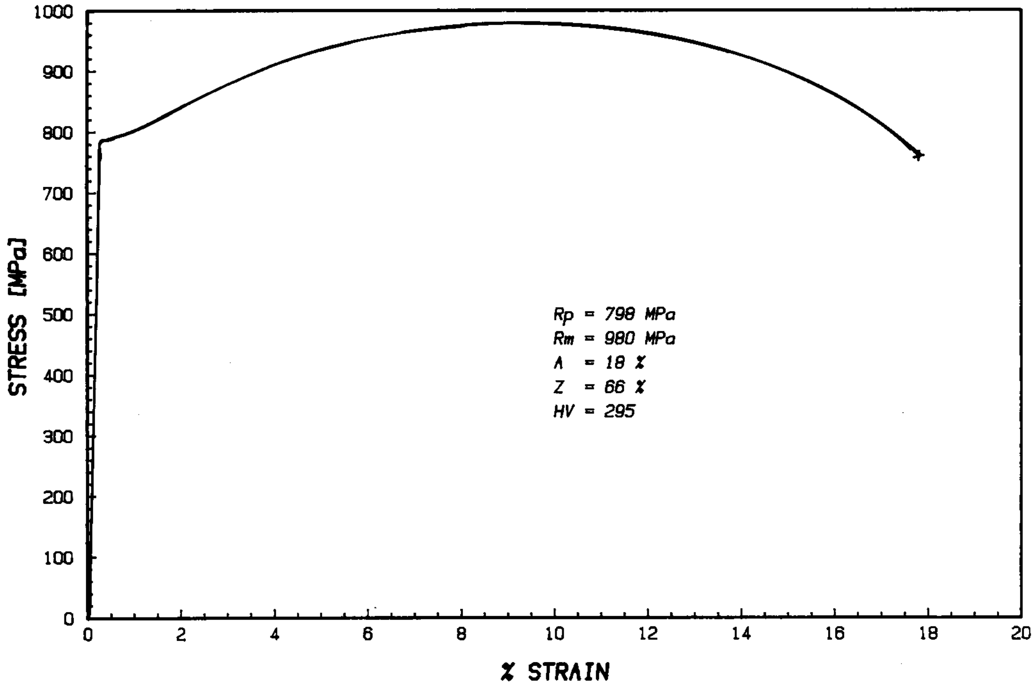

Fig. 4—A stress-strain curve for the steel as received

cyclic bending executed in a special jig in such a way that the amplitude of plastic strain at the surface was limited to 1,3 per cent. According to the Coffin–Manson[7,8] relationship, a fatigue life of about 500 to 1000 cycles can be expected at a strain of that amplitude. For the purpose of the experiment, 10 cycles of plastic bending were applied initially, and then again after 4 intervals of aging for 10 days at 100°C. In this way, a total of 50 cycles of low-cycle fatigue stressing was imposed interspersed with periods of aging. This simulated the influence of periodic overloading into the plastic range during the expected life time of the component, an overloading that might make it susceptible to strain-age embrittlement. In each instance, the V notch of the Charpy specimens was machined only after straining and aging.

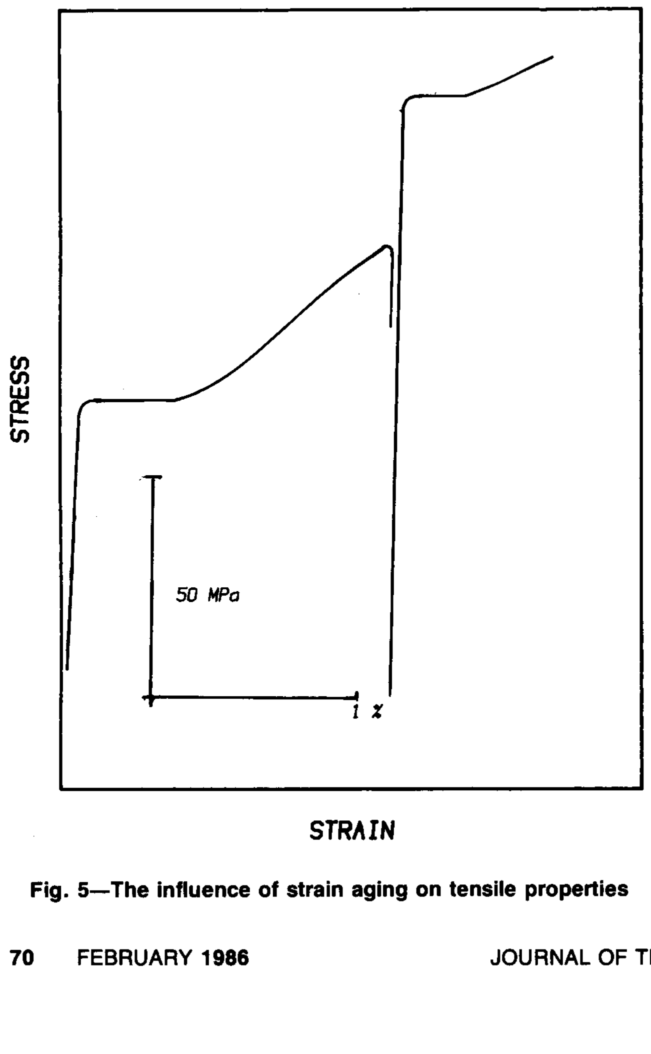

Fig. 5—The influence of strain aging on tensile properties

Fig. 6 shows the Charpy impact energy as a function of the testing temperature. The BTT of the steel as received was about −110°C. It also shows the influence of straining alone, as well as of strain aging, on the impact energy. The results show that workhardening due to straining, as well as the additional hardening due to strain aging, resulted in a slightly increased 'upper shelf' impact energy. Straining alone and strain aging resulted in an increase in the BTT (50 J) of about 10 and 15°C respectively. Thus, the increase in BTT due to the combined effect (strain aging) was 25°C, which is much smaller than the increase that can be expected for low-carbon structural steel (about 50°C).

Fig. 7 shows the corresponding results for specimens that were strained cyclically by bending interrupted by aging at various intervals. In many respects, the results obtained by cyclic bending are equivalent to those from monotonic straining. The increase in the BTT (25°C) was about the same as that found for monotonic straining.

Discussion and Conclusions

The results of the tests show that the susceptibility of a hardened, tempered low-alloy steel to embrittlement by strain aging as measured by the increase in BTT was approximately half the value that can be expected for low-carbon structural steel. For the limited range of experimental conditions used, the influence of periodic overloading by cyclic plastic straining during aging resulted in a rather insignificant increase in BTT. It can be concluded from these results that hardened, tempered

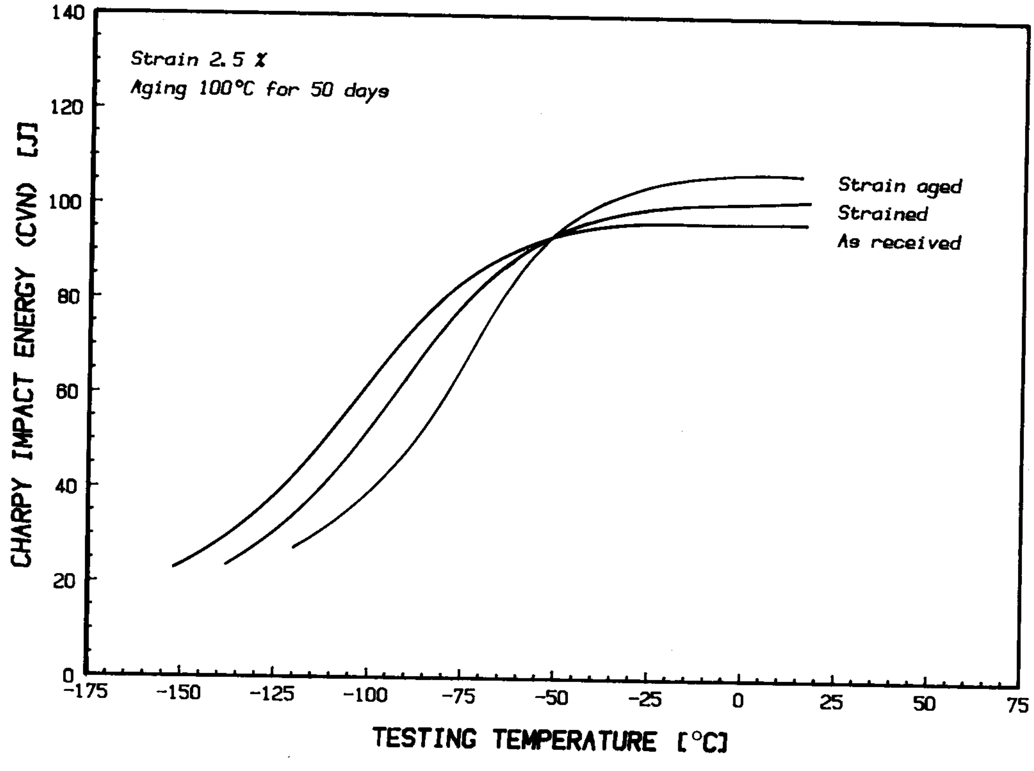

Fig. 6—The influence of strain and strain aging on impact-energy properties

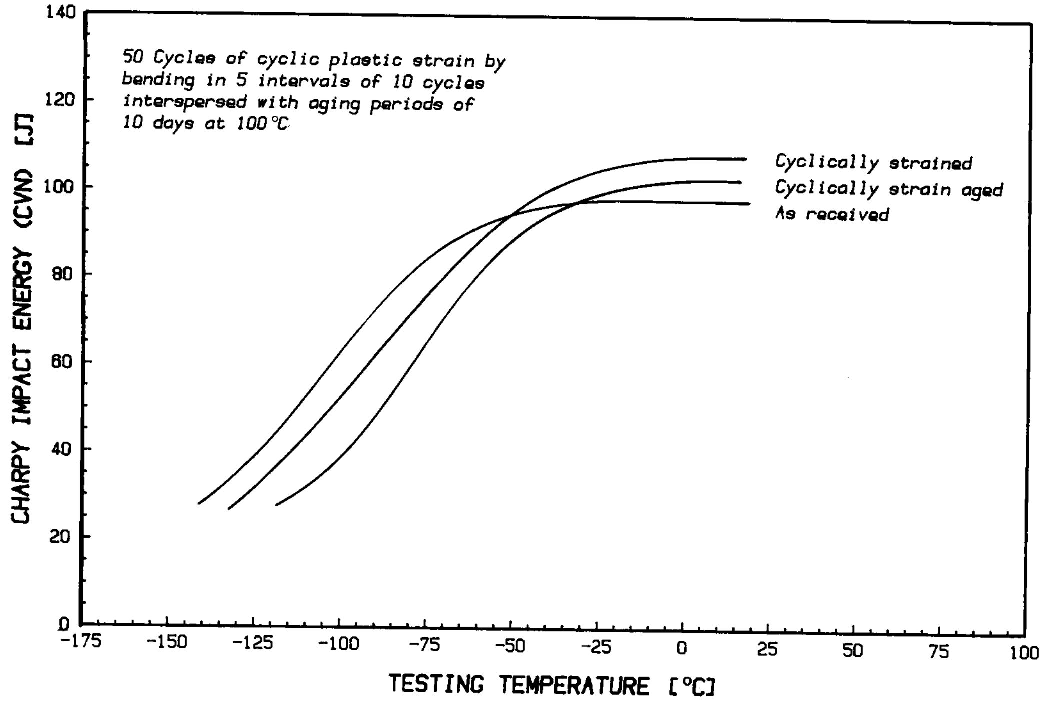

Fig. 7—The influence of plastic strain and concomitant aging on impact-energy properties

low-alloy steels are probably not unduly susceptible to strain aging.

Mangear, a low-carbon high-manganese structural steel, has been exempted from the statutory requirement of periodic annealing mainly on the grounds that the impact energy at room temperature is not affected by strain aging. In fact, Mangear is not an inherently non-aging steel, and it would probably be susceptible to embrittlement by strain aging as most steels are. However, the low-carbon content, coupled with the high manganese content (1,5 per cent) of Mangear, results in a material of low BTT. The resultant increase in BTT due to strain aging is therefore not sufficient to affect the impact properties at room temperature. In many respects, the same argument can be applied to hardened, tempered low-alloy steels. Properly hardened, tempered low-alloy steels are normally characterized by a very low BTT (−110°C in the present instance). Even after embrittlement by strain aging, the BTT is probably still lower than that of unembrittled Mangear. Clearly, such a steel is far superior to

Mangear and qualifies for the same exemption.

The requirement that a hardened and tempered steel should be annealed periodically to relieve the effect of possible embrittlement due to strain aging is without precedent in non-mining but equally critical applications. In the case of gun barrels, for example, the barrels are autofrettaged regularly by internal pressurization into the plastic state to increase their ability to withstand plastic deformation in use. In effect, the metal is used in the strain-age embrittled condition without the requirement for periodic annealing.

On the basis of the results obtained, it is recommended that components of hardened, tempered low-alloy steel should be exempt from the statutory requirement as long as the BTT of the material after heat treatment is $-25°C$ or less.

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Coal preparation

On 31st December, 1985, some 2700 envelopes were mailed worldwide (courtesy of Alberta Travel) to potential delegates and partners of the 10th International Coal Preparation Congress, which is to be held in Edmonton (Canada) from 31st August to 5th September, 1986. They were also mailed to participants of the International Coal Preparation Exhibition.

The package consisted of the following:

- The final Congress brochure, in the four Congress languages (English, French, German, Russian), contaiing the programme outline; the names of the ten members of the international committee; the times and dates of, and sponsorship credits for, the Sunday reception, the Monday banquet, and the Friday barbecue and rodeo; the ladies' programme; and the technical programme with 40 authors from 17 countries.
- The coloured tours brochure (in English only), issued by the David Thompson Country Tourist Council, the organizers of the 4 pre-Congress study tours, the 3 mid-week study tours, and the 3 post-Congress study tours. One pre-Congress tour is to the Nova Scotia coalfield and the Ottawa research laboratories; the others and the three post-Congress study tours are to coal-preparation plants in west-central Alberta (Yellowhead), and in south-east (East Kootenays) and north-east (Wolverine) British Columbia, all in the Canadian Rocky Mountains.
- The registration forms, in the four languages, for the Congress events, hotel reservations, tours (including the mid-week tours), and the International Symposium on Coal Transportation and the post-Symposium 3 days at Expo 86. Note: Brochures on the Symposium and on the Coal Preparation Exhibition will be mailed on request.
- 'Alberta Discovery Guide' with photographs of some of the world's most beautiful scenery and internationally famous Rocky Mountain Parks of Jasper and Banff—and of the unique Edmonton Convention Centre (overlooking the North Saskatchewan River), where the technical sessions, exhibition, and reception and banquet will be held.

The last day for early pre-registration is 30th June, 1986. Some of the events are restricted in number (e.g. the Wolverine post-Congress tour, due to the limited number of passengers on B.C. Rail Dayliner through the new Rocky Mountain electrified railway; and the Coal Transport Symposium, due to the hotel demand in Vancouver for Expo 86). Early return of the forms is therefore advisable. In addition, only early pre-registrants will have bound copies of the 40 papers, in their choice of language, awaiting their arrival in Edmonton.

If you have not yet received your package, please contact CIM at Suite 400, 1130 Sherbrooke Street West, Montreal, Quebec, Canada, H3A 2M8 (Tel: (514) 842-3461, Telex 055-62344) and request a copy.

The Congress theme is 'Coal Preparation: Impact of Environmental and Economic Factors'. With 12 of its 13 coal-preparation plants in the environmentally sensitive Rocky Mountains and foothills, and situated over 1000 km from the Pacific coalports, Canada is particularly aware of these world-wide concerns.