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# DEFORMATION OF TECHNICAL IRON

# IN THERMAL CYCLING

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In present - day machines and mechanisms, whose metal parts work hot, there are unavoidable temperature fluctuations which, under certain conditions, can considerably lower the strength. In the course of their life, the parts of jet propulsion devices suffer several hundred temperature changes. The effect of this, a considerable increase of creep, is usually overlooked in the design and use of the machines.

We have found that when tension is applied to specimens of technical iron containing 0.03% carbon, in which there is a longitudinal temperature gradient, superplasticity appears, indicated by the formation of two necks and by a vigorous progress of shearing deformation.

Before testing, the specimens were vacuum annealed for two hours at 1000°C (1830°F). Tests were made on an IMASh-5M machine [1-3].

Series of pyramidal micro-indentations were made along the longitudinal axis of the test specimen with a PMT-3 hardness tester, spaced about 50$\mu$ (0.002 in) apart; the indentations were made in the middle of the specimens, and also at 7-17.5 mm away in the portions where superplasticity arises. These distances were determined in preliminary experiments, which revealed the position of the endangered zones under particular thermal cycling conditions.

The specimens were heated by the passage of industrial frequency alternating current through them, conveyed through flexible copper leads with clips. This produced a longitudinal temperature gradient, with the highest temperature at the middle of the specimen. With an active cross section of 9 sq. mm and a length of the heated part of 46 mm, for example, 1000°C (1830°F) was maintained in the middle of the specimen over a length of about 12 mm and the temperature then gradually decreased towards the copper terminal clips. Fig. 1 shows the temperature distribution along a specimen of technical iron, with its middle zone heated to 800°C (1470) and 1000°C. The temperature varied from 400°C (750°F) at the clips to 1000°C in the middle.

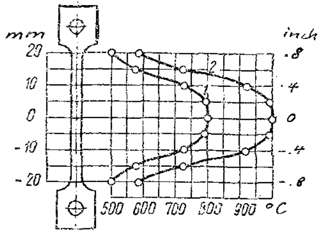


Fig. 1. Temperature distribution along technical iron specimen during resistance heating in vacuum.
1- heated to 800°C (1470F); 2- to 1000°C

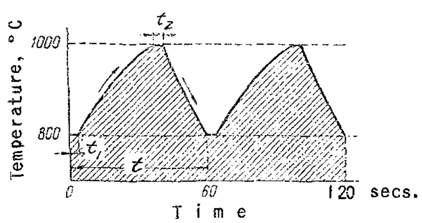


Fig. 2. Variation of temperature in middle of specimen during thermal cycling ($t_1 = t_2$)

Fig. 2 shows the thermal cycle employed. Each cycle lasted 60 seconds and consisted of a two second holding at 800°C ($t_1$), heating to 1000°C and holding there for two seconds ($t_2$), followed by cooling to 800°C. In an attempt to find the effect of holding time at maximum temperature on the superplasticity, the values of $t_1$ and $t_2$ were varied up to 60 seconds.

Cycling was automatic. The values of $t_1$ and $t_2$ could be continuously varied from 0 to two minutes with a motorized time relay. Under certain testing conditions, when thermal cycling was operative, two necks formed on the specimens symmetrically, in the zones of lower temperature. The explanation which can be advanced for these necks is as follows:

With an average 0.03% of carbon in the specimen, its percentage in individual parts of grains, particularly at their boundaries and at the block boundaries, can considerably exceed this 'mean' value. It has been convincingly shown [4] that when the total surface area of the grains increases in iron due to grain refinement, the solubility of carbon increases, which indicates segregation of carbon at grain boundaries. Autoradiograms with radiocarbon prove the presence of carbon at the boundaries of grains and blocks.

It can therefore be presumed that when there is a longitudinal temperature gradient in a specimen, the α-γ transformation will occur only locally, since as the carbon content increases, the temperature of this transformation falls. In the transformation, there is a 12.4% increase in the lattice parameter of iron from 2.861 to 3.5586 A (reduced to 20°C).

When the carbon content of austenite increases, the lattice parameter increases also, becoming 3.5650 A at 0.2%, 3.5714 A at 0.4%, 3.5778 A at 0.6%, 3.5842 A at 0.8%, and 3.6034 A at 1.4% [5].

Because of the non-uniform carbon distribution within the individual grains, and of the development of local centers in which the α-γ transformation occurs, interatomic forces are affected and the strength of the metal lowered.

One of the reasons for the formation of two necking zones is thought by Feltham to be movement of dislocations due to temperature gradients. This is supported, in particular, by the use of a temperature gradient in zone refining for metal purification.

A 'discontinuous' change in properties of iron at the transformation temperature can influence accelerated deformation. When iron changes from the α to the γ form, its strength, indexed for instance by its hardness, increases by almost 50% [6].

This idea that the main reason for 'superplasticity' of technical iron is local transformations in carbon-enriched zones, is illustrated by Fig. 3. When

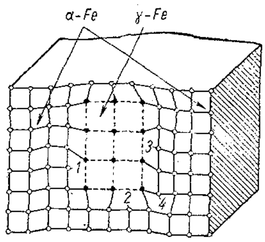


Fig. 3. Specimen of iron after local transformation reducing the interatomic bonds in the lattice (schematic).

the carbon-rich areas are heated to the α-γ transformation temperature (the carbon atoms are not shown in Fig. 3), γ phase with an increased lattice parameter is formed. Changes in the interatomic forces and the appearance of vacancies (1-4, Fig. 3) are evidently the main reasons for the sharp fall of strength. In the middle zone of the specimen, heated to 1000°C, the α-γ transformation can occur at any carbon concentration anywhere and carbon segregation does not cause superplasticity.

Fig. 4 shows a series of micrographs, taken from the same region of the surface of a specimen of technical iron during a static tensile test (0.33 kg/mm = 470 psi) at a constant temperature of 1000 °C (1830 °F). Fig. 4a shows the specimen surface prior to the tension test with the diamond point indentations on it, made with a 30 g. load. Arrows indicate the direction of tensile stress.

After 30 minutes, the austenite grain boundaries are clearly visible on the polished surface, Fig. 4b. Alongside fairly coarse grains, finer grains, indicated by arrows, have been formed.

During further holding at 1000 °C, the austenite grains grow, as can be seen on the succeeding micrographs taken after 1, 1-1/2, 2, 2-1/2, 3 and 4 hours. The grains noted on Fig. 4b have vanished, and after 4 hours' testing, the surface of the grains is comparatively smooth and there is no mutual displacement of grains. The total elongation of the zone studied, after test, is about 0.5%.

The microstructure in the middle of a specimen of technical iron subjected to thermal cycling between 800 and 1000 °C (Fig. 5) is almost the same. Fig. 5a shows the surface of the specimen before the test, arrows indicating the direction of the tensile stress; here the series of diamond indentations (20 g load) can be seen. The succeeding micrographs show the zone after 5-70 cycles of heating and reveal a characteristic fibrous texture inside the individual austenite grains.

Fig. 6 shows a series of micrographs, taken during an experiment from the same portion of the surface in a necked zone. Note the formation and gradual development of cracks in the zones denoted by arrows in Fig. 6, h, j.

Fig. 7 illustrates the deformation of a technical iron specimen in the middle zone where the temperature fluctuations were between 800 and 1000 °C, as well as in the neck, when the temperature passed from 720 to 850 °C. The total deformation in a neck at any instant is several times that in the hotter central zone.

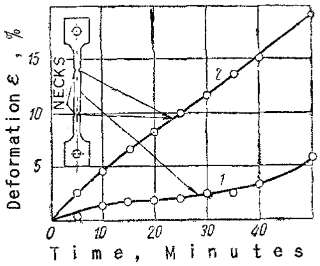


Fig. 7. Deformation of middle zone (1) and necks (2) of technical iron specimens under 0.33 kg/sq. mm tension and cycling between 800 and 1000 °C, in the middle zone

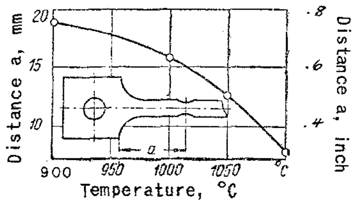


Fig. 9. Effect of maximum temperature level in the middle of a technical iron specimen on the distance between the necks and the edges of the specimens in thermal cycling.

In order to study the effect of the maximum temperature reached during cycling on the position of the necks, several experiments were run, in which the maximum temperatures were 850-1100 °C (1580-2010 °F) at 50 °C (90 °F) intervals. When the upper limit was 850 °C, one neck formed in the middle of the hot zone. At the upper limits, 900-1100 °C, the distances between the necks increased from 14 to 35 mm.

The appearance of the specimens subjected to cycling with various maximum temperatures, and with a constant lower limit of 800 °C (1470 °F) is in Fig. 8.

The systematic increase in the distance a from the edge of the specimen to the middle of the neck at various values of the temperature drop is shown in Fig. 9. This particular distance was chosen because the distance between the necks depends on the number of thermal cycles. Each point on the graph represents the results of five experiments.

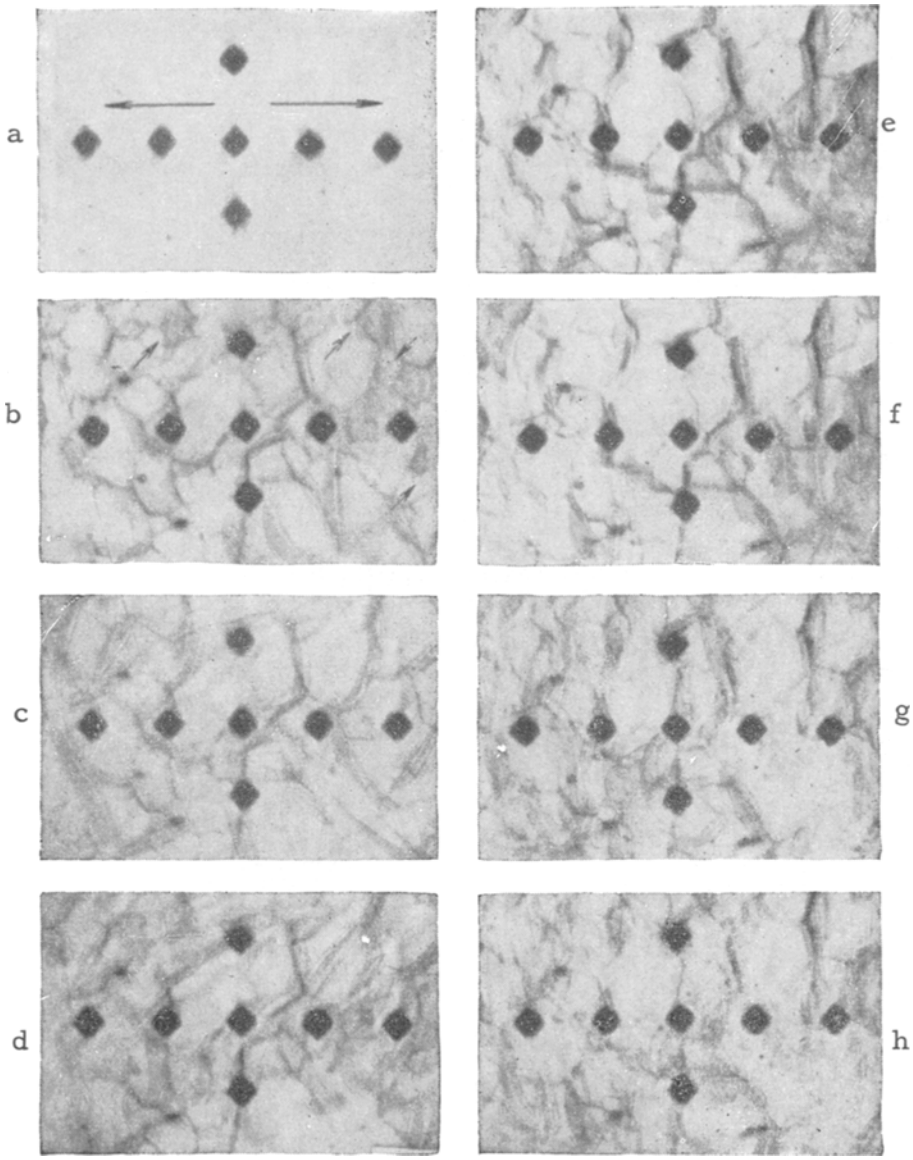


Fig. 4. Micrographs taken on surface of middle portion of specimens of technical iron during tensile test (0.33 kg/sq mm = 470 psi) and isothermal holding at 1000°C (1830°F). Magn. 204×

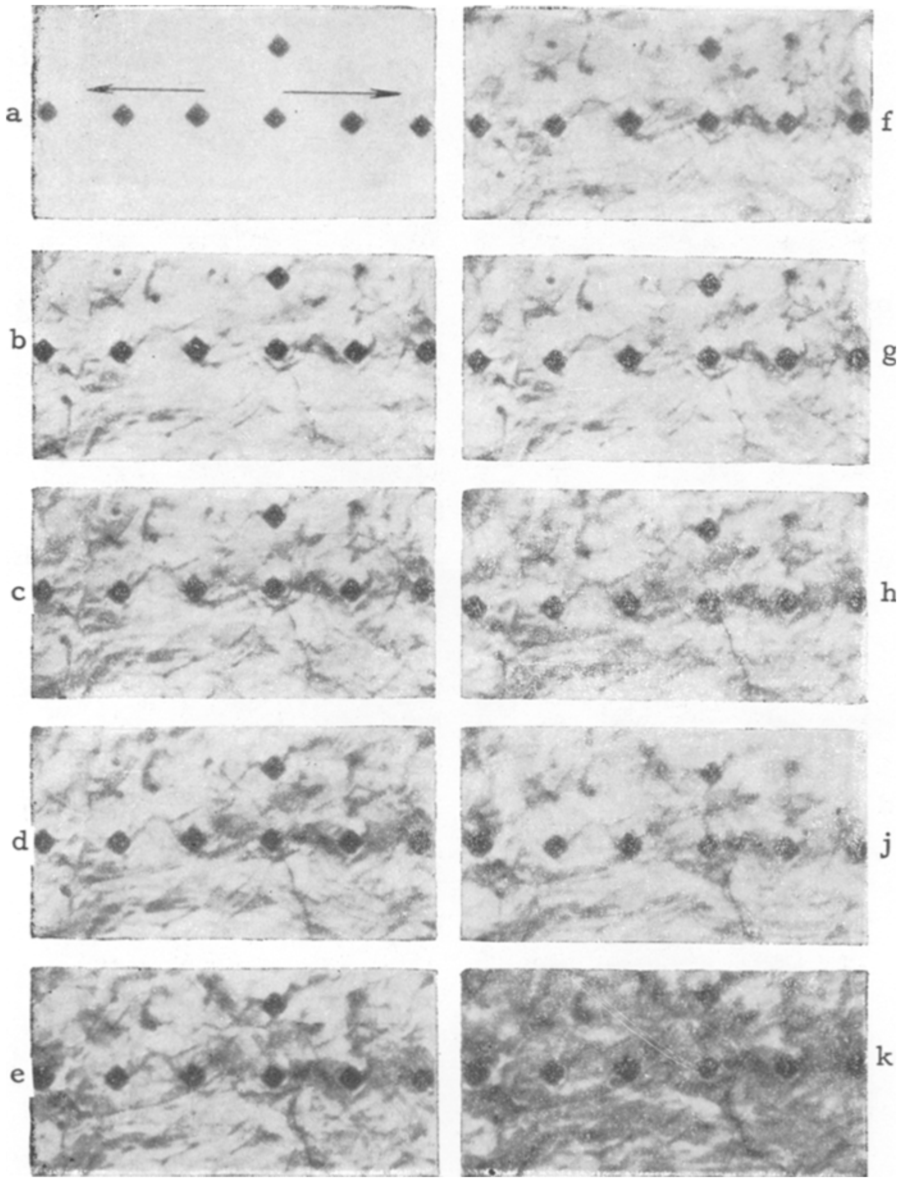


Fig. 5. Micrographs taken on surface of middle portion of technical iron specimens under tension (0.33 kg/sq. mm = 470 psi) and thermal cycling between 800 and 1000°C (1470 and 1830°F). Magn. 204×

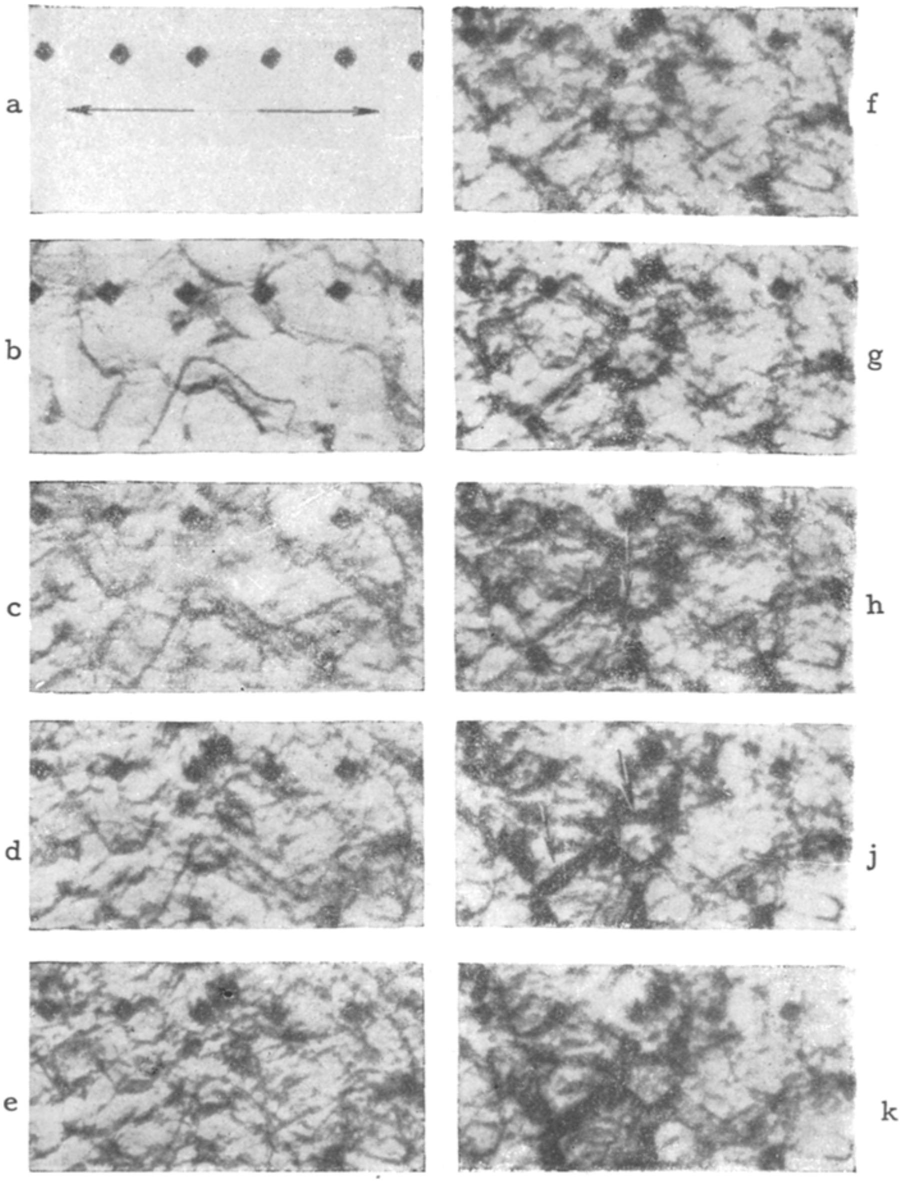


Fig. 6. Micrographs from surface of a technical iron specimen taken in a necked region formed during thermal cycling. Same notation as in Figure 5. Magn. 204×

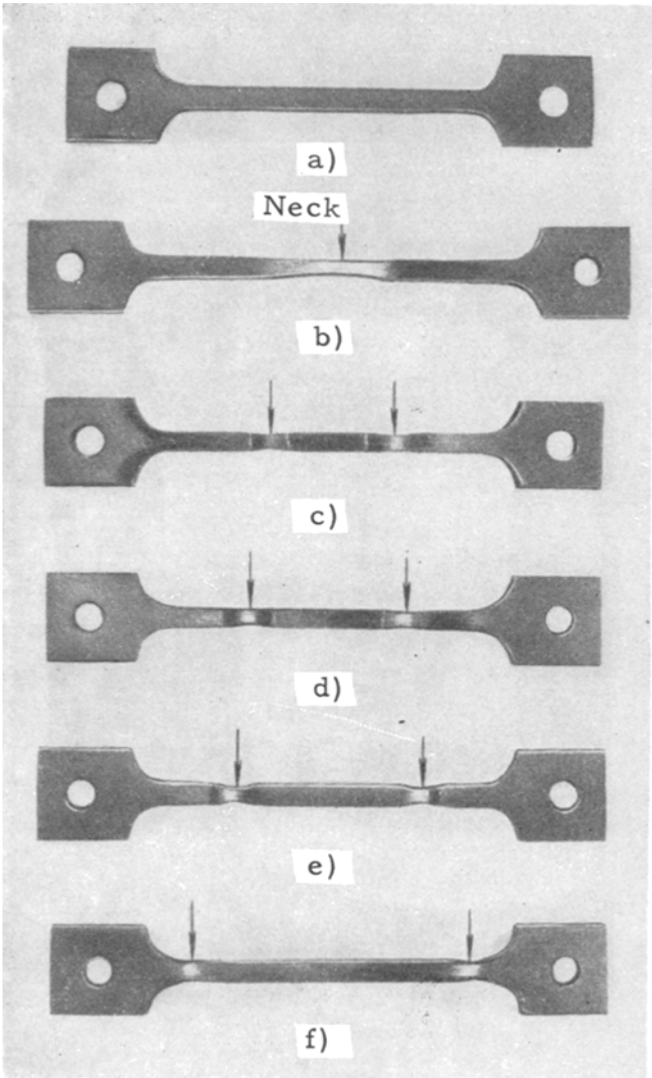


Fig. 8. Appearance of technical iron specimens: a- before test; b- after 150 cycles between 800 and 850°C (1470 and 1560°F); c- after 180 cycles, 800-900°C (1470-1650°F); d- 200 cycles, 800-950°C (1470-1740°F); e- 200 cycles, 800-1000°C; f- after 180 cycles, 1100-800°C (2010-1470°F). Constant tensile stress of 0.33 kg/sq mm. Actual size.

From Figs. 8 and 9, it can be seen that as the upper cycle temperature increases, a increases also. This can be attributed to an expansion of the middle zone (with a uniform temperature distribution). This zone is heated above the dangerous temperature, at which local α-γ transformations occur, resulting in 'superplasticity'.

When $t_1$ and $t_2$ are increased by a factor of 5 (to 10 seconds) and more, two necks are no longer formed.

These experiments convincingly show that to produce two necks in the lower temperature zones, one needs not only a definite temperature distribution along the specimen, but also a strictly controlled time of holding at the limiting temperatures. Such heating conditions can arise in parts of machines subjected to thermal cycling in service, and they can cause a sharp fall in strength and possibly failure.

## CONCLUSIONS

1. Under certain conditions of thermal cycling, a sudden reduction of the resistance to deformation is observed on specimens of technical iron, with formation of two necks on one specimen, in zones at 720-850°C (1330-1580°F).

2. The appearance of necks in zones at lower temperatures than in the middle can be explained by an irregular distribution of carbon inside the grains, and by its concentration along the boundaries of grains and blocks. With local heating and cooling of separate zones of the specimen to the α-γ transformation temperature, with lattice rearrangement, there will be a decrease of the interatomic forces leading to a sharp fall of the resistance to deformation only in the carbon-enriched parts.

3. Beyond certain lengths of the time of holding at the limiting temperatures, the phenomenon described is not observed.

## References


1 M.G. Lozinskii, Metalloved. i Obrab. Metallov., 1957 (11), 18-42.
2 M.G. Lozinskii, Izv. Akad. Nauk SSSR, Otd. Tekh. Nauk, 1957 (11), 14-26.
3 M.G. Lozinskij, Hutnické Listy, vol.12, 1957 (11), 974-85.
4 G. Lagerberg and A. Josefsson, Acta Metallurgica, vol.3, 1955, (3), 236-44.
5 S.F. Yur'ev, Specific Volumes of Phases in Martensite Transformation, Metallurgizdat, 1950.
6 M.G. Lozinskii and M.B. Guterman, ZAV. LAB., vol.22, 1956, (11), 1358-63 [HB Translation No. 4138].