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NATURE OF THE ANOMALOUS DEFORMABILITY OF LOW-CARBON STEELS

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The anomalous deformability of iron—carbon alloys has been investigated in many works. Some of them have noted the increase in the indices of plasticity (δ_5, ψ, n) with a simultaneous reduction in the flow stress (σ) close to the temperature of the Ac_1 phase transformation and the then following sharp decrease in plasticity with a simultaneous increase in the flow stress in the Ac_1-Ac_3 intercritical range.

The authors, having investigated the deformability of iron and steels in thermal cycling, related the anomalies in the properties to the occurrence of the $\alpha \to \gamma$-transformation [1, 2]. On the basis of the results of tensile and torsion tests, primarily of high-carbon tool steels, the author of [3] assumes that the effect of the increase in plasticity with a simultaneous reduction in the flow stress σ is characteristic of the subcritical range of temperatures of the pearlite transformation (up to A_1) and is related to the sharp decrease in the modulus of elasticity in the stage of pretransformation of the matrix. Accordingly, the subsequent reduction in plasticity and increase in flow stress must be observed in the A_1-A_3 intercritical range. Investigating the deformability of iron in torsion, the authors of [4] showed that in the 500-800°C range in deformation with certain degrees (ε) and rates ($\dot{\varepsilon}$) a reduction in the flow stress may also be obtained, which is related not to phase transformations but to the occurrence of the initial stages of dynamic recrystallization.

In this work an investigation of the phase transformations and also of the properties in tension, upsetting, and torsion in the 600-1100°C range was made on technical purity iron with 0.025% C and constructional steels containing up to 0.35% C. The steels were melted in an induction furnace and the 50-kg ingots obtained were forged into 10-mm bars (relative reduction 85-90%), from which were prepared special cylindrical samples for mechanical testing. In the original condition the steels had a ferritic—pearlitic structure with a grain size of 7-20 μm. The upsetting and tensile tests were made on samples with a gauge length diameter of 3 mm and lengths of 4 and 30 mm, respectively, on an IMASh 20-75 machine with a special attachment for compression of the samples at a constant loading rate. The 8-mm-diameter 50-mm-long torsion samples were tested on an SMÉG-10t machine. During the tests the force of deformation (P), the degree of deformation (ε), the time (τ), the temperature of the sample (t), and the change in the relative electrical resistance $(R_\tau - R_0)/R_0$ in the zone of deformation were recorded synchronously. Measurement of all of these parameters was done using a method similar to that described in [5]. The critical points in heating of the samples at rates from 7.5 to 200 deg/min were determined by the method of measurement of the relative electrical resistance directly on the IMASh 20-75 machine both during static heating and under dynamic conditions in deformation by tension and upsetting.

In heating of the samples and also in tension and upsetting of them four points, the Ac_{1s}, Ac_{1f}, Ac_{3s}, and Ac_{3f}, are clearly recorded on the curves of the change in electrical resistance [6] (Fig. 1). Between the Ac_{1f} and Ac_{3s} there is observed an interval of the "absence of transformation," which increases from 0 to 75°C with a reduction in the carbon content in the steel from 0.35 to 0.025%. The reasons for the existence in the intercritical area of such a temperature interval were discussed earlier by us [6].

Deformation during heating leads to displacement of the position of the critical points by 10-40°C in the direction of higher temperatures in tension and lower in compression (upsetting) (Fig. 1), which may be explained by the following. As is known [7], as the result of localization of deformation (formation of a neck) in tension and the low original ratio of length to diameter of the sample gauge length excluding loss of rigidity in upsetting

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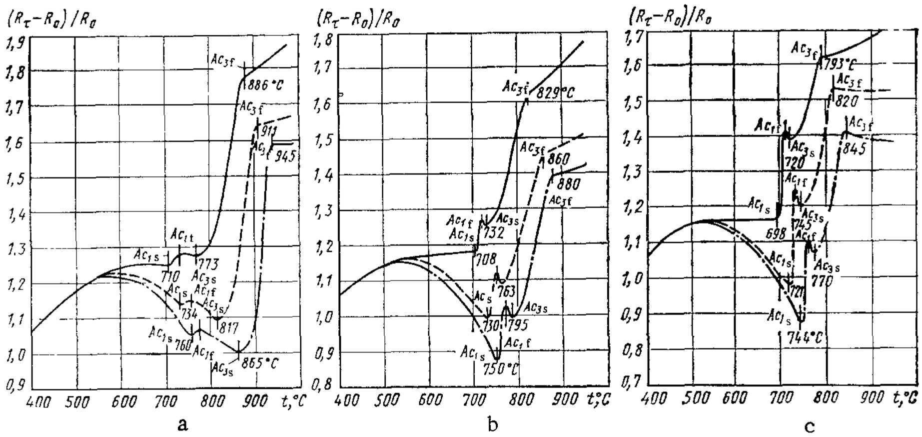

Fig. 1. Curves of the change in relative electrical resistance of of technical purity iron with 0.025% C (a), 10 steel with 0.138% C (b), and St3 steel with 0.205% C (c): broken lines) without deformation; dot-dash lines) in tension, $\dot{\varepsilon} = 1 \cdot 10^{-3}$ sec^{-1}; solid lines) in compression (upsetting), $\dot{\varepsilon} = 5 \cdot 10^{-3}$ sec^{-1}.

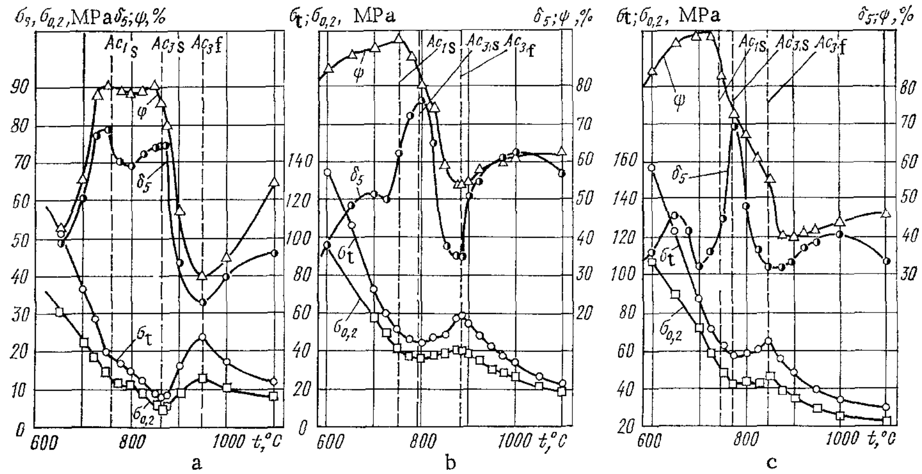

Fig. 2. Change in strength and plastic properties in tensile tests at a rate of $\dot{\varepsilon} = 1 \cdot 10^{-3}$ sec^{-1}: a) technical purity iron with 0.025% C; b) 10 steel with 0.138% C; c) St3 steel with 0.205% C; Ac_{1s}) start of transformation of pearlite into austenite; Ac_{3s}) start of austenitic transformation in the ferrite grains; Ac_{3f}) finish of the ferrite—austenite transformation.

a three-dimensional stressed condition is created in the zone of deformation. The more significant hardening of the surface layers in comparison with hardening of the volume of the sample during deformation [8] leads to the occurrence in the zone of deformation of primarily tensile or compressive stresses in tension and upsetting, respectively. In turn, with the occurrence of tensile stresses the $\alpha \to \gamma$-transformation accompanied by a decrease in volume is retarded while in the presence of compressive it is accelerated [9].

The results of tensile tests of technical purity iron and 10 and St3 carbon steels with a rate of movement of the clamps of 2 mm/min ($\dot{\varepsilon} = 1 \cdot 10^{-3}$ sec^{-1}) are presented in Fig. 2. For all of the investigated cases an anomalous relationship of the plastic (δ_5, ψ) and the strength (σ_t, $\sigma_{0.2}$) properties of the steels to deformation temperature is characteristic. Two maximums in the plastic properties, to which correspond reduced values of the resistance to deformation, which is especially well illustrated by the tests of technical purity iron, are observed (Fig. 2a). The maximums in the plastic properties for this material are observed in the intervals of 725-750°C (δ_5 = 74%, ψ = 85%) and 850-875°C (δ_5 = 68%, ψ = 80%).

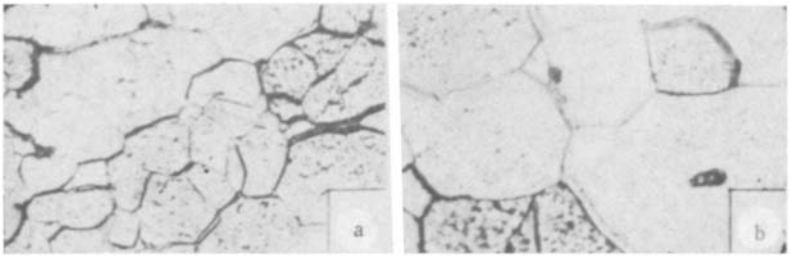

Fig. 3. Microstructure of technical purity iron in the zone of deformation of samples after tensile testing at a rate of $\dot{\varepsilon} = 1 \cdot 10^{-3}$ sec^{-1} in the temperature intervals of maximum plasticity: a) 725-750°C; b) 850-875°C (800 ×).

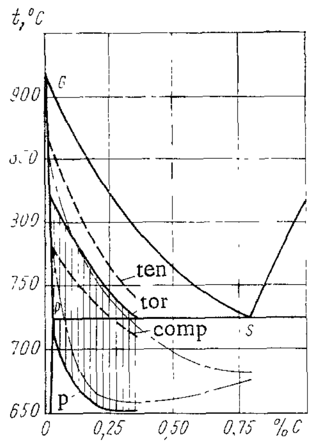

Fig. 4. Conditional position on the Fe—C diagram of the interval (shaded) of increased plasticity of carbon steels bound by the temperature of development of dynamic polygonization (p) and the start of formation of austenite in the ferrite grains in heating and torsion (tor), tension (ten), and compression (comp). The area bound by the dot—dash lines is the data of [11].

An analysis of the stress—strain curves obtained in tension of iron showed that in the 725-750°C interval the predominance of strain hardening in the initial stage ($\varepsilon \leqslant 5\%$) is replaced in the later stages by the predominance of dynamic softening. For the 850-875°C interval less significant strain hardening in the initial period ($\varepsilon \leqslant 3\%$) and the presence of a long steady stage of hardening-softening equilibrium in the latter period of deformation are characteristic. It should be noted that at higher temperatures the degree of strain hardening in the initial stages ($\varepsilon \leqslant 7$-10%) increases significantly, remaining high in the short steady stage of deformation, which leads to a reduction in the plastic properties and an increase in the deformation resistance.

The anomalies in deformability in tension studied using iron as an example are characteristic of carbon steels. The primary difference is the shift in the temperature interval of anomalous plasticity in the direction of lower temperatures and also a decrease in the effect of an increase in plasticity and a decrease in the strength properties in these intervals with an increase in carbon content in the steel (Fig. 2b, c).

In the microstructure of technical purity iron after deformation in the 725-750°C interval practically equiaxial subgrains within the ferrite grains are observed (Fig. 3a). The results of electron-microscopic investigations of the fine structure showed that the density of free dislocations within the subgrains is low. The dislocations are aligned in the polygonal walls, forming subboundaries. The disorientation of the subboundaries, determined from the aximuthal splitting of the reflexes on the microelectron-diffraction patterns, varied from 1-2 to 5-7°.

The structural features revealed are an indication of the development during tension of technical purity iron in the 725-750°C range of dynamic polygonization [10]. In this case dynamic polygonization is the basic mechanism of softening of ferrite after reaching the critical degree of deformation of 5-7%, which also leads to an increase in plasticity and a decrease in deformation resistance. After tension in the 850-875°C interval a subgrain structure is not observed and the average grain size of the ferrite increases (Fig. 3b). Obviously, in this interval a different mechanism of softening during deformation acts.

Taking into consideration the shift in the critical points in tension (shown by vertical broken lines in Fig. 2) we may speak of the full agreement of the maximum in plasticity of the steels not related to dynamic polygonization with the start of formation of austenite in the ferrite grains and the sharp reduction in plasticity with a simultaneous increase in deformation resistance with completion of this process, that is, with reaching of the Ac_3 point. In such a case the mechanism proposed by the author of [3] for explaining the subcritical superplasticity of steel is most probable. In accordance with this mechanism in the given case the reduction in deformation resistance and the increase in plasticity caused by the condition of pretransformation of the ferrite reach a maximum at the temperature of the start of intense increase in the low-plasticity newly formed austenite during the $\alpha \rightarrow \gamma$-transformation. The deformation resistance of the steel increases while the indices of plasticity drop until this transformation is completed. With an increase in temperature in the austenite area the deformation resistance of the steel decreases. The formation of eutectoid austenite from pearlite also leads to some reduction in the plastic properties, and the higher the pearlite content in the structure of the steel the greater the reduction (Fig. 2).

From this it follows that: 1) a reduction in deformation resistance and an increase in plastic properties of low-carbon steels in the intercritical (A_1-A_3) temperature interval may be obtained only with a carbon content of less than 0.35%, when a certain Ac_{1f}-Ac_{3S} temperature interval exists: 2) with a decrease in carbon content in the steel, when the ferrite will be in the pretransformation condition at a higher temperatures, it is natural to expect an increase in this effect (a reduction in deformation resistance and an increase in plastic properties), which must increase even more with the occurrence in the deformation process of a stressed state close to all-round tension promoting displacement of the critical points in the direction of higher temperatures.

During upsetting of steels at a rate of deformation of $1 \cdot 10^{-2}$ sec^{-1} as the result of the reduction in the temperature of the start of formation of austenite in the ferrite grains (Fig. 1) and approach of it to the temperature interval of dynamic polygonization in practice there occurs fusion of the two softening mechanisms considered, as the result of which in this case there is an increase in the indices of deformability of the steel. In the ferrite grains of the steels after upsetting there is observed a developed subgrain structure.

In torsion tests the presence of the maximum in plasticity not related to dynamic polygonization corresponds to the temperature of the start of the $\alpha \rightarrow \gamma$-transformation in the ferrite grains in static heating. Apparently, the presence of primarily tangential stresses does not lead to a shift in the critical points during plastic deformation.

On the basis of the results obtained in this work on the Fe—C diagram it is possible to conditionally separate the temperature—concentration area of increased deformability of low—carbon steels (Fig. 4). The upper boundary of this area, above the line PS, is determined by the start of the formation of austenite in the ferrite grains (Ac_{3S}). Below the line PS the area of increased deformability is bound by the temperature interval of development of dynamic polygonization in the steels. Between the upper boundary of the separated area and the line GS of the Fe—C diagram is located the interval of decreased deformability of the steels. With a carbon content in the steel of more than 0.35%, the area of increased plasticity is observed only below the line PS of this diagram. During deformation the position of the upper boundary of the area of increased plasticity above the line PS may shift upward or downward (in the presence of tensile or compressive stresses, respectively) relative to the equilibrium temperatures determined in static heating (without deformation). The established interval of increased deformability of low-carbon steels corresponds sufficiently well with the data of [11] obtained in investigation of the deformability of carbon steels (up to 1.0% C) in $600 \rightleftarrows 900°C$ thermal cycling under load with heating and cooling rates of 30-480 deg/min (Fig. 4).

Therefore, in the 600-1100°C interval in tension and upsetting of low-carbon steels, the anomalous increase in plasticity with a reduction in deformation resistance is apparently caused by two factors: 1) softening of the steel in development of dynamic polygonization in the subcritical (below A_1) temperature interval; 2) the condition of pretransformation of ferrite, in which its modulus of elasticity drops sharply. In the latter case the maximum increase in plasticity is reached at the temperature of the start of formation of austenite in the ferrite grains Ac_{3S}, which for steels containing less than 0.35% C is located in the A_1-A_3 intercritical interval, and the lower the carbon content in the steel, the higher the Ac_1 points. With a decrease in carbon content there is also an increase in the effect of an increase in the deformability of steel in the A_1-A_3 interval. An increase in the carbon content in the steel above 0.35% or displacement of the critical points in deformation under the influence of primarily compressive stresses promotes convergence or complete agreement of the temperature intervals of the action of the two mechanisms considered. The anomalous decrease in plasticity and increase in deformation resistance of the steels in the A_1-A_3 intercritical temperature interval is caused by the development of the $\alpha \rightarrow \gamma$-transformation in the ferrite. This effect reaches a maximum at the temperature corresponding to the critical point Ac_3.

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