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THE EFFECT OF GRAIN SIZE AND TEMPERATURE (77 to 293 K) ON THE LIMITING DISPLACEMENTS DURING THE SHEARING OF CARBON STEELS

S. DZIDOWSKI (WROCŁAW)

The effect of grain size on the limiting displacements due to localization of strains during shearing is described. Tests on carbon steels of 0.09 and 0.44% C content sheared at the temperature from 77 to 293 K were carried out. It has been found that the lowering of the temperature of shearing speeds up localization of strains, particularly at lower carbon contents in steel. As the temperature was lowered, a progressive decline in the influence of carbon content on the value of limiting displacements was observed. Refinement of structure delayed localization of strains in a manner practically independent of temperature. A general form of an equation which describes the simultaneous effect of temperature, grain size and carbon content on the limiting displacements of the material in the plane of shearing has been proposed.

1. Introduction

The problem of localization of strains has been the subject of numerous papers. Most of them deal with the tensile test and the process of sheet metal forming. The main aim of those papers was to formulate the criterion of global instability of the material and the distorted object or to determine the limiting strains. For these purposes, different approaches have been used, e.g. extreme, bifurcation and imperfect. A more detailed discussion and a critical review of most of the adopted approaches can be found in papers [1–4].

The shearing of metals has not been the subject of the above considerations, the only exception being the shearing in tensile and torsion tests [5, 6]. Analysis of the strains which occur during cropping of, for example, sheet metal or bars has usually been conducted in order to determine the force and the work of the shearing. For this purpose, relatively complex calculation methods necessitating certain simplifications have been applied. The simplifications affected, among other things, the description of the area of plastic strains.

The aim of the author of the present paper is to bind more closely the properties of the sheared material with the development and the distribution of strains in the zone of shearing [7] since it is the distribution of strains in the shearing zone that determines the distribution and the size of the external distortions of the sheared material. The latter determine, for example, the practical usefulness of the nonwaste shearing of materials by means of plastic working methods.

In one of his papers the author describes the development of strains in the material and proposes a criterion of the loss of stability during shearing. In most general terms, this instability is understood as an

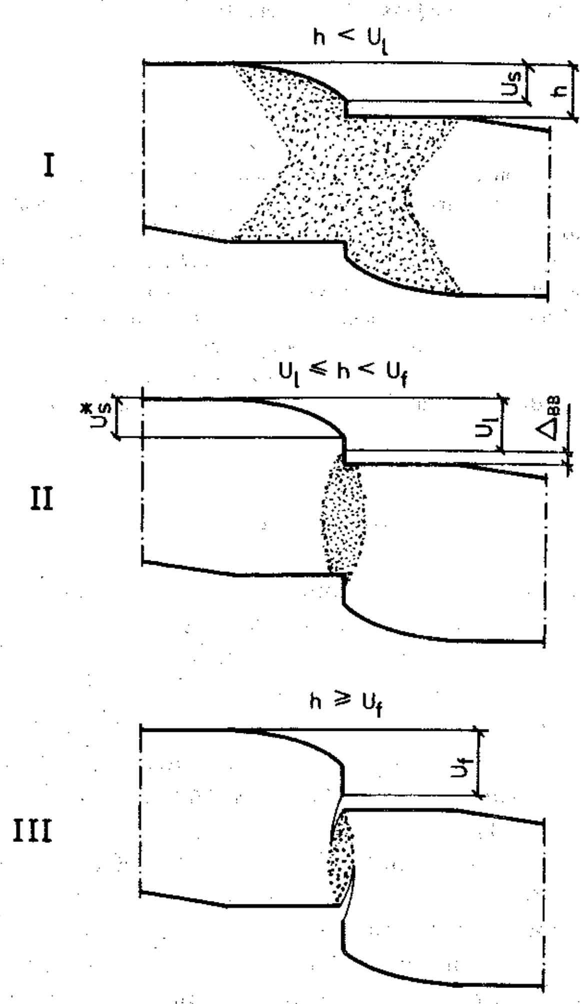

Fig. 1. Distribution of strains in the shearing zone: h — displacement of the shearing blade, U — displacement of the material in the plane of shearing, U_s — displacement of the free surface, U_s^* — maximum displacement of the free surface, U_1 — limiting displacement due to localization of strains, U_f — limiting displacement due to cracking, Δ_{BB} — increment of width of the burnished strip

interruption of the process of migration of strains (displacements) along the transversely sheared specimen. The result of such instability is the setting of boundaries of the area of the strains generated in the Ist stage of the process and an arrest of the increment of displacements U_s of the free surface (Fig. 1). This occurs at the moment when strains localize in a narrow band of the sheared material (stage II — Fig. 1). This moment corresponds to the maximum of the shearing force [7]. The maximum displacements of the material in the plane of shearing which correspond to the maximum of the shearing force have been denoted in Fig. 1 as U_1. Further displacement of the material ($h > U_1$) increases the width of the so-called burnished strip by the value of Δ_{BB} with no increment in the displacement U_s of the free surface. This goes on until cracks appear in the material (stage III — Fig. 1).

The aim of the present paper is to determine the effect of the structure on the value of displacements U_1 which are limiting due to the localization of strains in the shearing zone. From the technological point of view, localization of strains during shearing is an advantageous phenomenon [9] and as such requires further studies and description. In paper [8], a few methods of inducing localization of strains are discussed. One of them consisted in the cooling down of the sheared material. However, there is a risk involved which is associated with the brittleness of the material at low temperatures. Hence the attempt to answer the question to what extent refinement of structure — which eliminates brittle cracking — will influence the development and the value of limiting displacements in the range of temperatures from 77 to 293 K.

2. Test material and methods

The tests were carried out on $d = 22$ mm diameter round bars made of carbon steels of 0.09% and 0.44% C content. The chemical constitution of the studied steels and their initial mechanical properties can be found in paper [8]. This time, the steel of 0.09% C content was subjected to additional heat treatment in order to refine its structure.

Two kinds of heat treatment were used. The first consisted in heating the steel up to the temperature of about 1163 to 1193 K followed by cooling together with the furnace. In this way grain size no. 8 was obtained. The second heat treatment consisted in heating the steel up to the above temperature and water-cooling. Then the steel was annealed at the temperature of about 953–973 K for 60 min. and cooled together with the furnace. In this way grain size no. 9 was obtained. The structures of the studied steels are shown in Figs. 2 and 3.

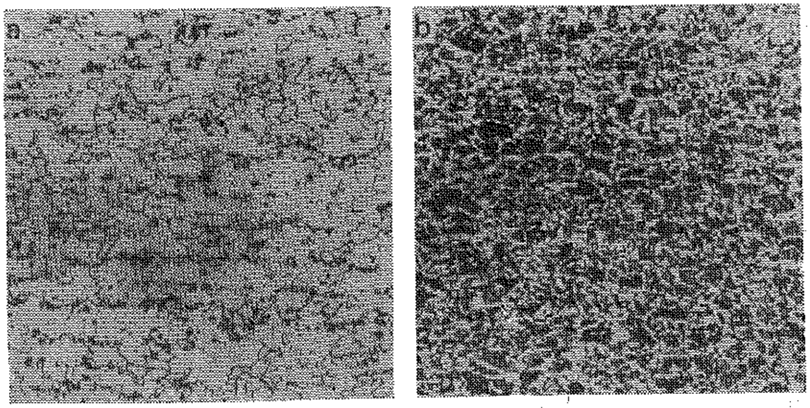

Fig. 2. Initial structures of the tested steels: a) steel 0.09% C — grain size no. 2–no. 7 (65% of no. 2); b) steel 0.44% C — grain size no. 7, Magnification 100×. Reduced to 0.64 of original size

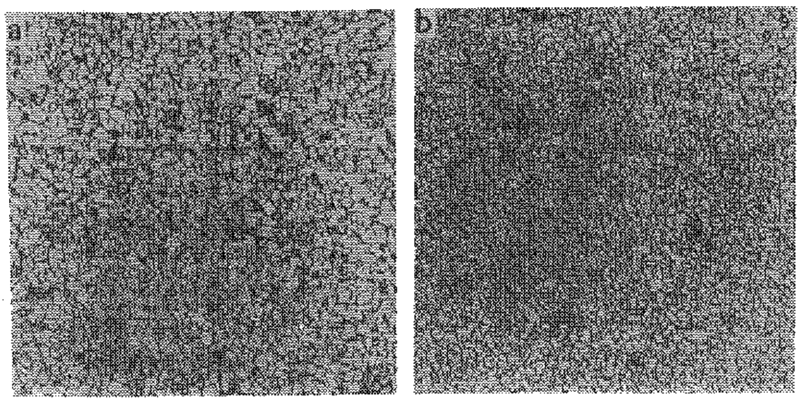

Fig. 3. Structures of steel 0.09% C after heat treatment: a) grain size no. 8; b) grain size no. 9. Magnification 100×. Reduced to 0.64 of original size

Shearing was conducted at the temperature from 77 to 293 K. The temperatures were obtained by directly cooling the test pieces in liquid nitrogen or appropriate baths: alcohol and a hydrocarbon one. The baths were precooled with liquid nitrogen and its vapours. The length of the test pieces was $l = 2d = 44$ mm. The test pieces were sheared into halves. The interblade clearance of the circular shearing tool was 0.6 mm. The shearing force as a function of the shearing tool's travel was recorded by means of an oscilloscope and a photographic camera. The oscilloscope recorded the signals coming from a strain gauge dynamometer and from an induction sensor of displacements, which were installed in the shearing device.

The value of U_1 displacements — limiting due to localization of strains — was measured on oscillograms of the shearing force. At the same time, displacement U_1 was a coordinate of the maximum of the shearing force recorded as a function of displacement U determined in the plane of shearing (Fig. 1).

3. Test results and discussion

The results of the studies have been rendered graphically and described by experimental-mathematical relationships. Figure 4 shows the influence of temperature T on the value of displacement U_1 — limiting due to the localization of strains in carbon steels of 0.09% and 0.44% C content. It follows from Fig. 4 that the lowering of temperature from 293 to 77 K speeds up localization of strains in the tested steels. The value of displacement U_1 decreases exponentially by 68% for 0.09% C steel and by 50% for 0.44% C steel as the temperature is lowered. The characteristic phenomenon here is the occurrence of clear differences between the values of U_1 for steels 0.09% C and 0.44% C in the ambient temperature of 293 K and almost total absence of such differences at the temperature of liquid nitrogen of 77 K. This is due to the fact that as the temperature of the sheared material is lowered, the influence of carbon content on the value

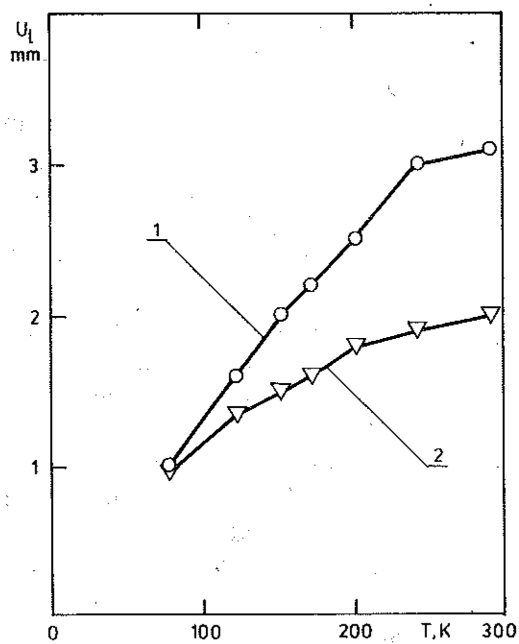

Fig. 4. The effect of shearing temperature T and carbon content on the value of displacement U_1 — limiting due to strain localization. Carbon content: *1* - 0.09% C, *2* - 0.44% C.

of displacement U_1 diminishes. This phenomenon has important practical implications. Mainly, it makes possible the precision shearing of steels of different carbon content at the same sufficiently low temperatures. This cannot be said about shearing at ambient temperature. At ambient temperature, a bar made of low-carbon steel is subject to distortions which sometimes make the whole technology of plastic shearing meaningless.

The obtained results (Fig. 4) can be presented in a convenient form if they are described by the following linear relationship:

$$U_1 = A + B \log T, \tag{3.1}$$

where U_1—limiting displacement, A and B — constants, T — temperature in Kelvin degrees.

A graphic representation of the relationships (3.1) obtained for steels 0.09% C and 0.44% C is shown in Fig. 5 which also contains experimental data. The measuring points mapped onto Fig. 5 correspond to mean value obtained from 6–12 test pieces. The good correlation between the experimental results and their mathematical approximation indicates that in some cases, similar tests will not have to be conducted in the full range of temperatures 77 to 293 K.

In Fig. 6 the effect of grain size of steel 0.09% C on the value of displacements U_1 in the range of temperatures from 77 to 293 K is presented. The graph was plotted on the basis of the relationship (3.1) and the results of an experiment carried out only at the temperatures of 77 and 293 K. As it follows from Fig. 6, refinement of structure delays strain localization — the value of displacement U_1 grows. The straight lines in Fig. 6, corresponding to the particular grain sizes, are parallel to each other. This shows that increments of displacements U_1 in this case are not dependent on temperature but only on the grain size of the given steel. From the practical point of view, therefore, a fine-grained structure of steel should be avoided if the displacements U_s of the free surface of the sheared material are to be small. In the case of shearing at low temperatures, however, the size of grains cannot be increased indiscriminately since coarse-grained structures are conducive to brittle cracks localized outside the adopted plane of shearing [9].

The above analysis of test results proves that the simultaneous effect of temperature and carbon content and grain size of steel on the value of the displacements U_1 which are limiting due to the maximum of the shearing force can be described in a general way by means of the relationship (3.1). The particular constants in the equation of a straight line (3.1) acquire physical meaning. The angle of inclination of the straight line reflects the effect of carbon content on limiting displacements in steel during shearing. Grain size, on the other hand, determines the value of the

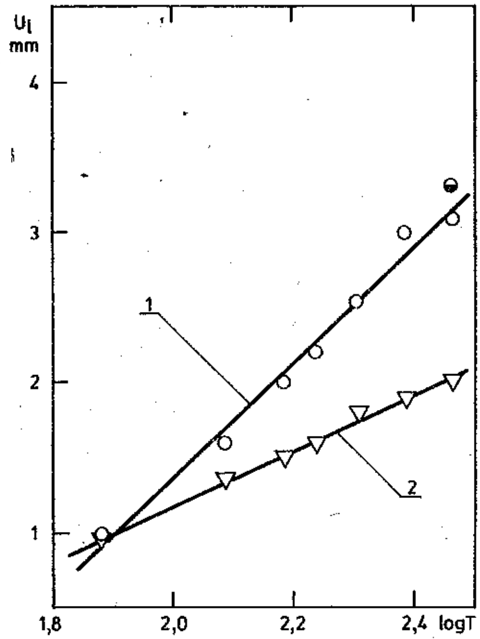

Fig. 5. The relationship between displacement U_1 and the logarithm of shearing temperature T and carbon content in steel: *1* - 0.09% C; *2* - 0.44% C.

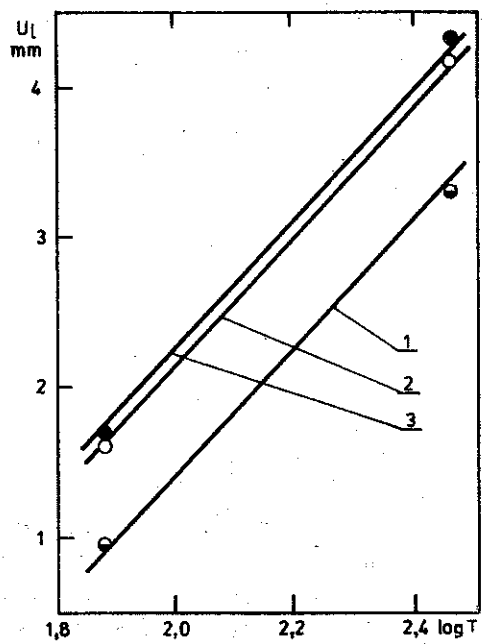

Fig. 6. The relationship between displacement U_1 and the logarithm of shearing temperature T and grain size. Steel of 0.09% C content. Grain size: *1* - no. 2 - no. 7 (65% of no. 2); *2* - no. 8; *3* - no. 9.

second constant a in the above equation. This can be written as follows:

$$U_1 = A_z + B_c \log T, \tag{3.2}$$

where A_z — constant dependent on grain size, B_c — constant dependent on carbon content.

In the case of the tested steel 0.09% C, the constants in Eq. (3.2) assume the following approximate values depending on the grain size:

a) grain size no. 2–7 (65% of grain size no. 2)

$$U_1 = -7.14 + 4.25 \lg T, \tag{3.3}$$

b) grain size no. 3

$$U_1 = -6.32 + 4.25 \lg T, \tag{3.4}$$

c) grain size no. 9

$$U_1 = -6.21 + 4.25 \lg T. \tag{3.5}$$

The relationships from Eqs. (3.3) to (3.5) describe the effect of temperature T on the displacements U_1 — limiting due to localization of strains at the maximum of the shearing force. They do not distinguish the localization associated with Lüders strain which can occur earlier. In the considered case, refinement of the structure of steel 0.09% C and the lowering of temperature to 77 K gave a clearly marked yield point. Lüders strain was observed mainly on the oscillograms of the shearing force for steel 0.09% C having grain size no. 9. However, the value of the Lüders displacement corresponding to this grain size was within the limits of the measuring error.

4. Conclusions

On the basis of the performed studies of the process of shearing of carbon steels of 0.44% C and 0.09% C content and different grain size, the following conclusions as to the limiting displacements during plastic shearing in the range of temperatures from 77 to 293 K have been drawn:

1. The lowering of the temperature of the material from 293 to 77 K speeds up considerably localization of strains which starts after the shearing force reaches its maximum. The relationship between the limiting displacements U_1 and temperature has the character of an exponential function.

2. As the temperature is lowered, the influence of carbon content on the value of the displacements U_1 limiting due to localization of strains diminishes.

3. Refinement of steel structure delays localization of strains in a manner which is practically independent of temperature.

4. The effect of temperature, carbon content and grain size on the value of the limiting displacements of the tested steels can be described by a linear relationship. The independent variable of this relationship is the logarithm of temperature. The tangent of inclination of the considered straight line is determined by the carbon content in the steel and the value of the constant depends on the grain size. The angle of inclination of the straight line grows as the carbon content in the steel decreases and the value of the constant increases as the grain size is decreased.

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Streszczenie

WPŁYW WIELKOŚCI ZIAREN I TEMPERATURY NA PRZEMIESZCZENIA GRANICZNE PODCZAS CIĘCIA STALI WĘGLOWYCH

Omówiono wpływ wielkości ziaren na przemieszczenia graniczne ze względu na lokalizację odkształceń podczas cięcia. Badania przeprowadzono na stalach węglowych 0,09 i 0,44% C ciętych w temperaturach od 77 do 293 K. Stwierdzono, że obniżenie temperatury cięcia przyśpiesza lokalizację odkształceń tym bardziej, im niższa jest zawartość węgla w stali. W miarę obniżania temperatury obserwowano postępujący zanik wpływu zawartości węgla na wartość przemieszczeń granicznych. Rozdrobnienie ziaren opóźniło natomiast lokalizację odkształceń w sposób praktycznie niezależny od temperatury. Zaproponowano ogólną postać równania opisującego jednoczesny wpływ temperatury, wielkości ziaren i zawartości węgla na graniczne przemieszczenia materiału w płaszczyźnie cięcia.

Резюме

ВЛИЯНИЕ ВЕЛИЧИН ЗЕРЕН И ТЕМПЕРАТУРЫ НА ГРАНИЧНЫЕ ПЕРЕМЕЩЕНИЯ ВО ВРЕМЯ РЕЗКИ УГЛЕРОДИСТЫХ СТАЛЕЙ

Обсуждено влияние величин зерен на граничные перемещения из-за локализации деформаций во время резки. Исследования проведены на углеродистых сталях 0,09 и 0,44% С резанных в температурах от 77 до 293 К. Констатировано, что снижение температуры резки ускоряет локализацию деформаций тем больше, чем более низким является содержание углерода в стали. По мере снижения температуры наблюдалось поступающее исчезновение влияния содержания углерода на значение граничных перемещений. Размельчение зерен замедляло же локализацию деформаций способом практически независящим от температуры. Предложен общий вид уравнения описающего одновременное влияние температуры, величин зерен и содержания углерода на граничные перемещения материала в плоскости резки.

INSTITUTE OF MACHINE BUILDING TECHNOLOGY
TECHNICAL UNIVERSITY OF WROCŁAW.

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