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BY

M. BRANDES

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DETERMINATION OF THE COHESIVE STRENGTH OF LOW-CARBON STEEL (0.03% C) BY MEANS OF HIGH HYDROSTATIC PRESSURES

Marek Brandes*

ABSTRACT

Using an extrapolation of tensile data obtained under varying amounts of hydrostatic compression to positive hydrostatic pressure (hydrostatic tension), the cohesive strength of a low-carbon steel (0.03% C) has been determined. These preliminary results indicate a value of 54.6 kg/mm^2, somewhat lower than obtained by other investigators. Increased strength with decreasing temperature occurs and is consistent with other observations.

INTRODUCTION

The term cohesive strength or brittle fracture strength means the critical value of the normal tensile stress causing a fracture of the material in the range of its elastic strain. Direct measurement of the cohesive strength of ductile materials is however extremely difficult, and for some metals quite impossible. The reason for these difficulties is the occurrence of large shearing stresses during tensile tests; these stresses in turn cause plastic deformations and strain hardening of the investigated materials.

For many years, investigations have been carried out to determine the cohesive strength of ductile metals.(1-4) In order to obtain a brittle fracture of ductile metal specimens without its plastic deformation (i.e. in the range of its elastic strain), experiments have been made by stretching notched specimens at room temperature, and with smooth cylindrical specimens at very low temperatures. In some cases notched cylindrical specimens have been stretched at low temperatures. Dynamic (explosive) loadings have also been applied to determine the cohesive strength of metals.(5)

All the above-mentioned methods gave only approximate values of the initial cohesive strength of ductile metals. The approximations obtained were caused by the increase of cohesive strength at falling temperatures,(6-7) and by the fact that the determined values of cohesive strength depend on the geometry of the specimen notch.(3)

Determining cohesive strength by using the dynamical (explosive) loading method created great technical difficulties. According to estimates of some investigators(8) and recently by this author values for cohesive strength obtained in such a way are "considerably higher than the tensile strengths which are determined statically."(9,p.322)

For some mild metals like copper, nickel, aluminum, and bronze and for some steel types, for example austenitic stainless steels, the determination of the cohesive strength was not possible even in an approximate form. Even the sharpest and deepest notches machined on the investigated specimens, as well as the lowest temperatures applied during these tests, created no possible way to obtain a brittle fracture in those kinds of metals. For example, at liquid hydrogen temperature (20°K), stretched copper (99.7% Cu) cylindrical specimens showed, prior to fracture, a cross-section reduction of 75%,(6) nickel (99.4% Ni) showed 64%,(6) cast phosphor-bronze showed 39.0%,(6) and the austenitic stainless steel (IHI8N9T) showed a reduction of 48.0%.(7)

Applying the method presented in ref. 10 for determining the technical cohesive strength of ductile metals by means of high hydrostatic pressures, it was possible to determine in a relatively exact way (± 2.0%) the technical cohesive strength of low-carbon steel (0.03% C).

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* Instytut Mechaniki Precyzyjnej, Warsaw, Poland.

The results of these investigations are presented in this paper.

METHOD OF INVESTIGATION

The experimental equipment used to investigate the mechanical properties of metals under high hydrostatic pressures (up to 30,000 kg/cm^2) has been reported previously in detail.$^{(11\text{-}13)}$

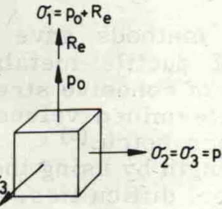
The determination of the cohesive strength of metals by means of high hydrostatic pressures was based on an experimental evaluation of the functional dependence existing between the hydrostatic pressure p inside the pressure chamber where the cylindrical specimens have been stretched, and the natural reduction in area $\bar{\epsilon}_v$ of the stretched specimens $\bar{\epsilon}_v = \ln S_o/S_u$ (where S_o is the area of the original cross-section, and S_u the smallest cross-section of the stretched specimen).

As was shown by Bridgman (14) and others (15,16), as well as by the results presented in this paper, the function $p = f(\bar{\epsilon}_v)$ is a rectilinear one beginning from the atmospheric pressure $(p = 0)$ up to a certain pressure which is characteristic for a given metal.

The first part of the rectilinear function $p = f(\bar{\epsilon}_v)$, determined when using different pressures, has been extrapolated up to such a value of the positive hydrostatic pressure $p_o > 0$ (hydrostatic tension) at which the natural reduction in area $\bar{\epsilon}_v$, becomes equal to zero, and corresponds with the vanishing of the neck and with the brittle fracture of the specimen.

The rectilinear dependence of the natural reduction in area $(\bar{\epsilon}_v)$ upon the hydrostatic pressure $(p < 0)$ should not change its (rectilinear) character when the ambient pressure changes its sign to a positive one. (10)

The triaxial tension existing in the center of the cross-section of the stretched specimen at the vanishing of the neck is shown schematically in Fig. 1.



$$R_o = \sigma_1 = p_o + R_e;\ \sigma_1 - \sigma_3 = R_e;$$
$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2R_e^2$$

Fig. 1. Stress components acting on the cross-section of stretched specimen at the vanishing of the neck (p_o - hydrostatic tension, R_e - yield stress in tension).

According to the results of the analysis of the stress state existing in the minimum cross-section of a specimen stretched under high pressure, (10) the cohesive strength R_o of the investigated material is equal to $R_o = p_o + R_e$ (where p_o is the positive hydrostatic pressure value determined experimentally, and R_e the yield stress in tension of the material).

The pressure existing inside the pressure chamber where the test pieces were stretched was constant and showed minimal changes during the tensile tests (± 20 kg/cm^2). (12) The pressure chamber was connected with a precise Bourdon tube pressure gauge having the required range of pressure. The pressure gauge used for these tests has been verified by means of a free piston Basset monometer.

The minimum diameter of the specimen was measured using a precise Zeiss comparator after taking the specimen out of the pressure chamber.

The results obtained have been plotted on a diagram of coordinates $(\bar{\epsilon}_v, p)$.

The equation of the initial (first) part of the straight line function $p = \alpha + \beta\, \bar{\epsilon}_v$, established for the investigated metal, was based on the measured pressure values p and the natural reduction values $\bar{\epsilon}_v$, applying the method of least squares.

From this equation, $(p = \alpha + \beta\, \bar{\epsilon}_v)$, the value of the hydrostatic tension $p_o = \alpha$ has been calculated, when the natural reduction in the area of the stretched specimen should become equal to zero $(\bar{\epsilon}_v = 0)$.

SPECIMENS USED

The specimens were machined from steel bars normalized at 930° C for 1.5 hours. The chemical composition of the applied steel and its mechanical properties at atmospheric pressure are given in Table 2. The grain size of the investigated steel corresponds with ASTM 4.

The specimen size is as follows:

original diameter $d_o = 4.5 \pm 0.05$ mm
original length $L_o = 15 \pm 0.1$ mm

The stretching rate was 11 mm/min; the temperature was ≅ 20° C.

RESULTS OBTAINED

The values obtained by measuring the pressure p in kg/cm² and the natural (logarithmical) reduction in area $(\bar{\epsilon}_v = \ell n\, S_o/S_u)$ are given in Table 1.

TABLE 1

Pressure p kg/cm²	Natural reduction in area	Pressure p kg/cm²	Natural reduction in area
0	1.31	1600	1.94
0	1.36	1600	1.83
0	1.29	1600	1.82
900	1.62	2000	2.02
900	1.63	2000	2.00
900	1.62	2000	1.97
1300	1.78	2500	2.13
1300	1.73	2500	2.24
1300	1.75	2500	2.26

Fig. 2 shows in graphical form the function $p = f(\bar{\epsilon}_v)$, characterizing the investigated low-carbon steel. As can be seen, the function is rectilinear.

Due to the invariability of the pressure during stretching tests, the scattering of the obtained points is relatively small (± 2.0%). The equation of the straight line found by the method of least squares is as follows:

$$p = 36.1 - 27.9\, \bar{\epsilon}_v$$

At the value of $\bar{\epsilon}_v = 0$, p equals $p_o = 36.1$ kg/mm². The determined value $p = p_o > 0$ for $\bar{\epsilon}_v = 0$ corresponds with the value of a hydrostatic tension at which the tested specimens, loaded additionally with an axial tensile stress equal to the stress yield in tension R_e, should break without plastic deformation $(\bar{\epsilon}_v = 0)$. The value for the investigated material is $R_e = 18.5$ kg/mm².

According to the evidence given in ref. 10, the initial cohesive strength R_o of a metal not strain-hardened equals $R_o = p_o + R_e$.

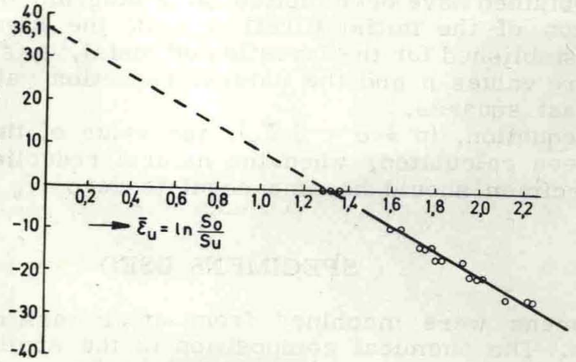


Fig. 2. Effect of hydrostatic pressure on the ductility of low-carbon steel (0.03% C). ($\bar{\varepsilon}_v$ - true strain, p - hydrostatic pressure kg/mm^2.)

The value of the initial cohesive strength or the so-called brittle fracture strength of low-carbon steel (0.03% C) at room temperature, determined in this way is equal to:

$$R_o = 54.6 \text{ kg/mm}^2$$

DISCUSSION

Other investigations aimed at measuring directly the cohesive strength of mild steel types at room temperature have not been successful. Only at very low temperatures was it possible to bring these steel types to brittle fracture and to determine their tensile strength. Table 2 contains

TABLE 2

No.	Chemical composition		Mechanical Properties at room temperature ($\approx 300^oK$)			Investigation temperatures ^oK	Cohesive strength R_o kg/mm^2	Sources
	C %	Other elements %	R_m kg/mm^2	R_e kg/mm^2	Z %			
1	0.03	-	30	18	76	20	89	(7)
2	0.035	Mn-0.02 p-0.003 S-0.016	32.1	-	73	93	78.7	(17)
3	0.04	-	-	22	-	(see stress-temperature curve, Fig. 4)		(18)
4	0.03	Mn-0.08 p-0.017 S-0.015	32.3	18.5	73.3	300	54.6	The present investigation

R_m - ultimate stress, ($R_m = P_m/S_o$); R_e - yield stress in tension; Z - reduction in area in %; $Z = (S_o - S_u)/S_o \cdot 100$.

a comparison of the brittle fracture strength values of low-carbon steel obtained by other investigations (7,17,18) by stretching the specimens at very low temperatures, with the values of the cohesive strength determined in the present investigations. The chemical compositions and mechanical properties of the compared low-carbon steels are similar.

As shown in Table 2, the value of the cohesive strength of low-carbon steel at room temperature determined in the present investigation is lower than the corresponding values of the brittle fracture strength obtained by stretching test pieces at very low temperatures. Such a relation was not difficult to provide because the results of many investigators (6,7,18,19) have shown that the brittle fracture strength rises when the temperature decreases.

The value of the cohesive strength of low-carbon steel (R_o = 54.6 kg/mm^2), obtained in the present investigation, was a confirmation of the increase mentioned above. This value created the possibility to establish in a quantitative form the increase rate (R_o/T) of the cohesive strength R_o, when the temperature decreases from the room temperature to a very low value (20°K). (R_o - cohesive strength, T - temperature.) The increase of the cohesive strength R_o in the case of the investigated steel type (0.03% C), amounts to about 1.25 kg/mm^2 for every 10°K of temperature decrease, i.e. about 2.3% of the cohesive strength value at room temperature. Elding and Collins (19) have shown that the dependence of the brittle fracture strength of steel AISI-1020 (0.2% C) upon the temperature forms a straight line in the range of temperatures lower than the ductile brittle transition temperature. The results of these investigations (19) are shown in Fig. 3.

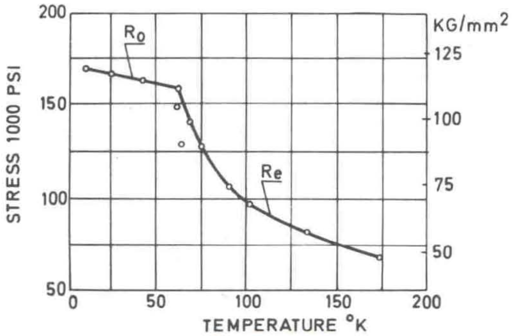


Fig. 3. Variation of brittle strength R_o, and yield stress R_e at low temperature of 1020 steel. (19)

It was interesting to check the position of the determined value of the cohesive strength R_o at room temperature in comparison with the corresponding values of brittle fracture stress found by other investigators at low temperatures. As shown in Fig. 4, the determined value of the cohesive strength at room temperature finds its place almost on a straight line (dotted lines) which is characteristic for the brittle fracture strength at low temperatures.

The cohesive strength of such low-carbon steel (0.03%) has not yet been determined at temperatures higher than the ductile-brittle transition temperature (about 80°K) where the yield stress is lower than the brittle fracture stress.

Some experiments have been carried out attempting to determine the cohesive strength of low-carbon steel (0.03% C) at room temperature when using notched specimens. (7) The author concluded that the value of the cohesive strength should be approximately higher than 56 kg/mm^2.

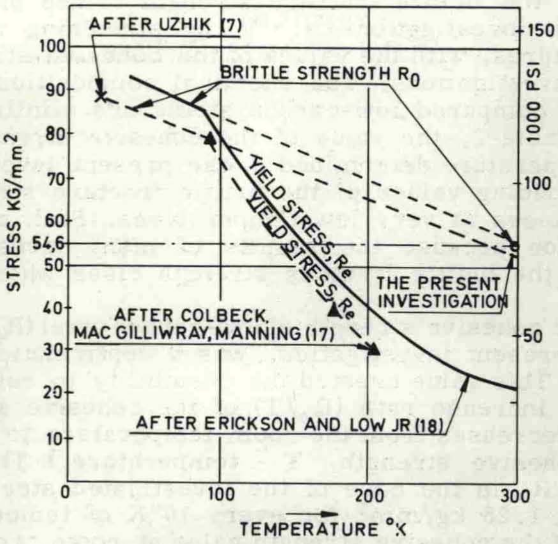


Fig. 4. Comparison of the cohesive strength (brittle strength) R_o of low-carbon steel (0.03% C) determined at room temperature with the brittle strength of similar steels (0.03 - 0.04% C) at low temperatures. (R_o - brittle strength, R_e - yield stress.)

CONCLUSIONS

1.) The initial cohesive strength of a non strain-hardened low-carbon steel (0.03% C) at room temperature, has been determined by high hydrostatic pressures to be $R_o = 54.6$ kg/mm^2.

2.) This value is lower than the values of brittle fracture strength determined by other investigators by means of stretching specimens at very low temperatures.

3.) A comparison of the obtained values of brittle fracture strength at different temperatures shows a linear increase as the temperature decreases. This is in agreement with the observations made by Elding and Collins in the case of steel 0.2% C.

4.) The increase of the cohesive strength for the investigated low-carbon steel (0.03% C) amounts to about 1.25 kg/mm^2 for every 10°K of the temperature decrease.

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RÉSUMÉ - La force de cohésion d'un acier à faible carbone (0,03% C) a été déterminée par extrapolation des données de traction, obtenues pour diverses valeurs de la compression hydrostatique à une pression hydrostatique positive (tension hydrostatique). Ces résultats préliminaires indiquent une valeur de 54,6 kg/mm^2, valeur quelque peu inférieure à celles obtenues par d'autres chercheurs. On constate un accroissement de la force pour une diminution de la température et ceci est conforme à d'autres observations.

ZUSAMMENFASSUNG - Durch Extrapolation von Zugspannungsdaten, welche unter verschiedenen hydrostatischen Drücken erhalten wurden, auf den Positivwert des hydrostatischen Druckes (hydrostatische Dehnung), wurde die Kohäsionsfestigkeit von kohlenstoffarmen Stahl (0,03% C) bestimmt. Die vorläufig erhaltenen Ergebnisse ergeben einen Wert von 54,6 kg/mm^2, der etwas niedriger liegt, als die bisher von anderen Forschern erhaltene Werte.

In Uebereinstimmung mit anderen Beobachtungen nimmt mit fallender Temperatur die Festigkeit zu.