DYNAMIC MECHANICAL PROPERTIES OF DUCTILE CAST IRON MATERIALS FOR THICKWALLED COMPONENTS

Wolfram Baer, Ralf Häcker and Johannes Börrnert
Federal Institute for Materials Research and Testing (BAM)
Unter den Eichen 87, D-12205 Berlin, Germany
E-mail: wolfram.baer@bam.de

Abstract

The present study is part of an ongoing research program of BAM in the field of fracture mechanics and component safety. This programme is focused on the systematic mechanical and fracture mechanical characterization of ductile cast iron materials (DCI) under dynamic loading conditions and the improvement of the relevant testing methods. The investigations presented here started with systematic work concentrating on details of the dynamic tensile test method, like specimen instrumentation, measurement of load, optical and strain-gage measurement of strain and data analysis. Resulting from this, an optimized testing method has been established for dynamic tensile tests on DCI materials. First results of systematic investigations on mechanical material properties of DCI under dynamic loading conditions are reported. Characteristics for the dynamic strength and deformation behaviour are discussed in dependence on the parameters pearlite content of the DCI matrix, test temperature and strain-rate. Furthermore, the effect of these influences on the dynamic true stress-strain curves is pointed out.

Introduction

DCI materials are used for safety relevant components in the fields of nuclear related and conventional technology in an increasing extend. Examples for safety relevant applications are turbine casings or rotating parts of transport systems like railway wheels. Furthermore, in Germany, DCI materials have been used very successfully for transport and storage casks for radioactive materials for more than 25 years. Due to new developments in cask design and efforts to extend the application limits the German safety assessment concept for these thickwalled components has been improved recently [1].

The improved safety concept incorporates a complete fracture mechanical safety assessment which has to cover all possible loading conditions in normal service as well as with accident conditions. Component failure by brittle or stable crack initiation has to be excluded in all cases. The practical application of this approach requires the detailed knowledge of the deformation and failure behaviour of DCI and the availability of both, loading parameters as well as material characteristics in terms of fracture mechanical quantities. Efforts are made in both areas especially in order to do further research work on dynamic loading conditions. At present, there are no standards available for the determination of dynamic mechanical material characteristics at all. For use with dynamic tensile tests only a first procedure with recommendations was published, ESIS P7 [2].

In order to determine the necessary loading parameters and to evaluate the mechanical behaviour of the component numerical simulation methods are developed, Zencker *et al.* [3], Enderlein *et al.* [3]. Nevertheless, for the prediction of valuable results these tools inevitably require the availability of proper mechanical material data like true stress-strain curves as input taking into account influences like microstructure of DCI, temperature and strain-rate. Furthermore, dynamic mechanical material properties are needed within the determination of dynamic fracture mechanical characteristics of DCI, Baer *et al.* [5], Müller *et al.* [6]. Examples are the derivation of crack initiation toughness values from dynamic crack resistance curves based on the dynamic blunting line or evaluation of adjusted limits for fatigue precracking.

Investigated Material

A favourite goal of the present investigations was to study the influence of the pearlite content of DCI on the mechanical behaviour. Therefore, three DCI materials with varying pearlite contents in the matrix of 0 %, 10 % and 20 % were investigated, Fig. 1. The material designation according to the German material standardization is EN-GJS-400. In the following the materials are referred to as GJS (0), GJS (10) and GJS (20).

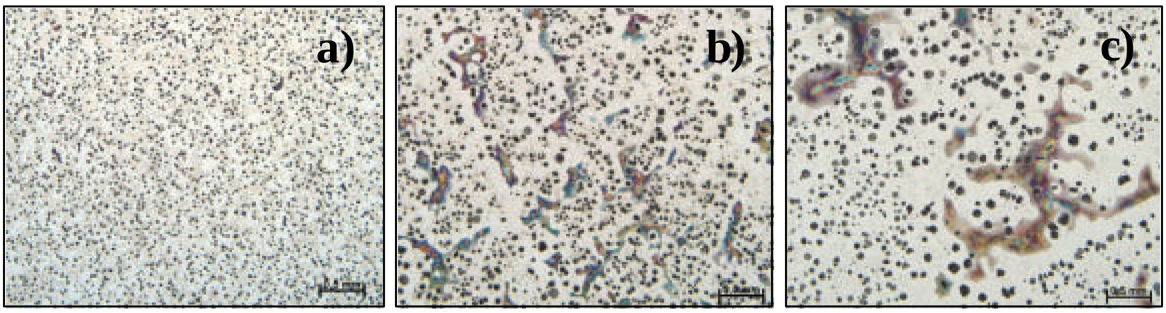

FIGURE 1. Metallographic images of the investigated DCI materials with pearlite content of 0 % (a), 10 % (b) and 20 % (c).

Additionally, microstructural parameters describing the size, morphology and distribution of the graphite nodules in the matrix have been determined by means of quantitative microstructural analysis, Table 1.

TABLE 1. Microstructural parameters of the investigated DCI materials.

Material	V_P / %	V_G / %	N_G / 1/mm^2	d_G / µm	λ / µm	f	d_F / µm
GJS (0)	0 (1-3)	10.8	161	30	42	0,87	19
GJS (10)	10 (6-12)	10.9	86	40	52	0,85	15
GJS (20)	20 (13-25)	12.3	43	56	73	0,86	14

V_P – mean pearlite volume fraction with range of single specimen values in brackets, V_G – graphite volume fraction, N_G – graphite nodule count, d_G – mean diameter of graphite nodules, λ – mean distance of graphite nodules, f – graphite shape parameter ($f \leq 1$, $f = 1$ spherical shape, $f < 1$ deviation from spherical shape), d_F – ferrite grain size

Experimental Procedure

Test Set-up and Test Method

The tensile tests were performed using two different test systems in dependence on the strain rate. A conventional closed-loop servo-hydraulic testing machine was used for quasi-static tests at 0.0001/s and at strain rates of 1/s. The tests at strain rates of 100/s and 250/s were carried out with a servo-hydraulic high-speed test system of the type Instron VHS with a maximum force of 50 kN and a maximum piston speed of 25 m/s, Fig. 2. Furthermore, a fast jaw grip system was used to minimize dynamic signal ringing. Specially designed tempering devices based on liquid nitrogen cooling were used for the low temperature tests at –40 °C. The tensile tests were performed according to the DIN EN 10002 standard [7] and by adopting the ESIS P7 procedure [2]. With the quasi-static tests B10x50 tensile specimens were used according to DIN 50125 standard [8]. At strain rates of 1/s and above B8x40 specimens [8] with additional dynamometer section were tested.

Basic requirements for reliable and precise results of dynamic tensile tests are proper solutions for the measurement of force and strain. These techniques have to be adjusted and optimized not only to the test conditions but also to the material. In contrary to steels, DCI materials offer elevated requirements to strain gage techniques due to their heterogeneous microstructure. The graphite nodules are sectioned at the specimens surface. During plastic deformation the nodules debond from the matrix and comparably large, growing cavities are formed thus decreasing the adhesiveness of strain gauges. Therefore, different measuring techniques were investigated concerning force and strain measurement and an optimized test method was established.

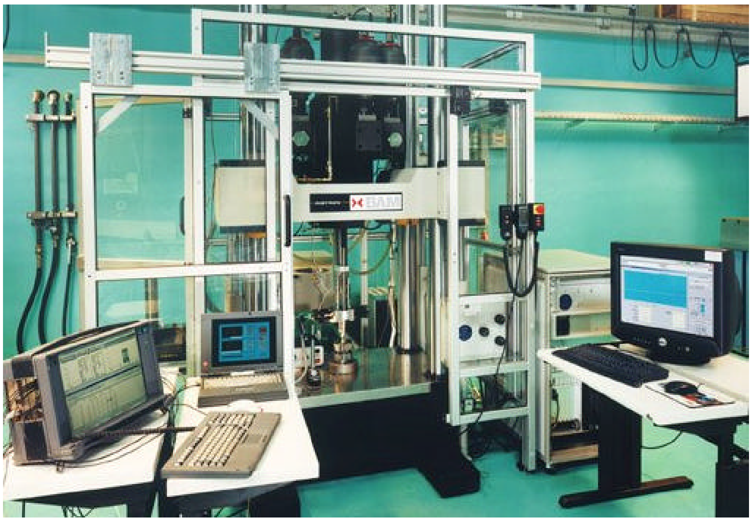

FIGURE 2. Servo-hydraulic high-speed test system, maximum force 50 kN, maximum piston speed 25 m/s.

Differences of the results of force measurement techniques at higher strain rates are underlined by Fig. 3. The closer to the specimen the load measurement is done the better becomes the signal since the registered oscillations decrease. Therefore, it is strongly recommended not to measure the force with standard piezoelectric load cells at strain rates above approximately 1/s. Within the present investigations the force measurement in the tests at 100/s and above was realised by strain gages at the specimens dynamometer sections. All strain gages had been calibrated statically before the tests. Up to 1/s standard load cells were sufficient.

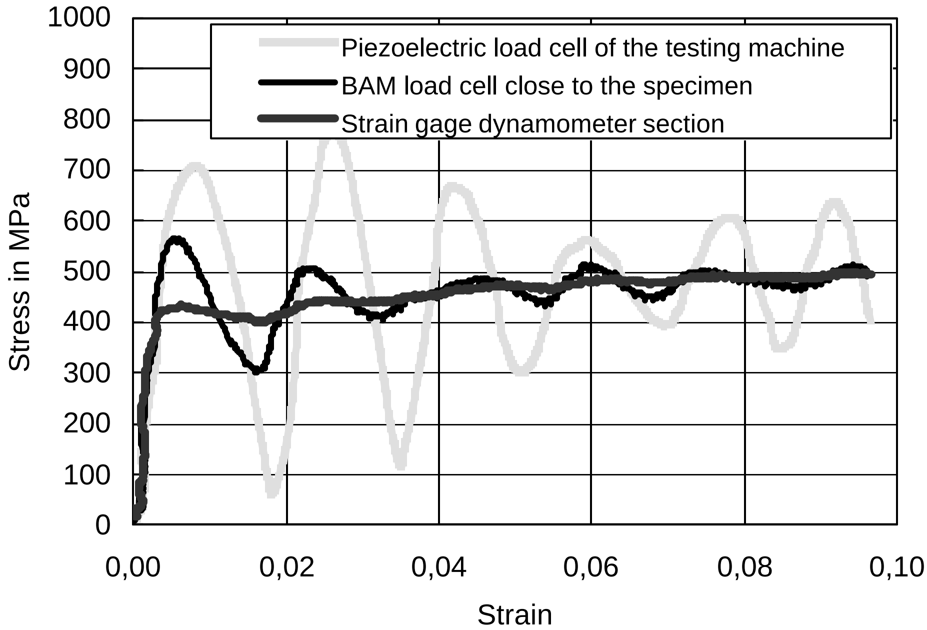

FIGURE 3. Force measurement techniques and resulting engineering stress-strain curves, GJS (0), ambient temperature, strain rate 100/s.

Standard clip-on extensometers were used for the local measurement of strain up to 1/s and an electro-optical extensometer (Zimmer camera) at higher strain rates. Global measuring techniques such as LVDT do not provide sufficiently precise results and are not recommendable. Different techniques with strain gages on the specimens gage length were examined. These techniques work well up to approximately 4 % of strain and provide the best way for determination of yield point values. Furthermore, all specimens were provided with grids so that the elongation at rupture values A could be determined according to [7].

Test Programme

Table 2 gives an overview of the test programme. In the test matrix the parameter strain rate denotes the plastic strain rate as it is defined by the mean value between the yield point and the ultimate tensile force. On average, 3 specimens were tested at one test condition. As results, the material characteristics 0.2 proof stress $R_{p0.2}$, ultimate tensile strength R_m (UTS), elongation at rupture A and the reduction of area Z according to [7] were deduced. Furthermore, true stress-strain curves were determined up to the point of ultimate tensile strength.

TABLE 2. Tensile test programme.

Material	Strain rate / 1/s			
	0.0001	1	100	250
GJS (0)	AT -40 °C	AT -40 °C	AT -40 °C	AT -40 °C *)
GJS (10)	AT -40 °C	AT -40 °C	AT -40 °C	AT -40 °C
GJS (20)	AT -40 °C	AT -40 °C	AT -40 °C	AT -40 °C *)

AT – ambient temperature, *) ongoing tests

Results and Discussion

An overview on the strength and deformation characteristics of the investigated materials at -40 °C and different strain rates is given in Fig. 4. Basically, the correlations are similar with ambient temperature so that the discussion within this paper is limited to -40 °C. Both, an increase in strain rate as well as an increase in the pearlite content lead to significantly reduced deformation characteristics. With respect to the strength characteristics, a notable strain rate sensitivity is found in the investigated range. Higher strain rates lead to higher strength values. Especially, this is the case with the 0.2 proof stress values. In contrary, a major influence of the pearlite content on the strength values was not found in the investigated range of microstructure.

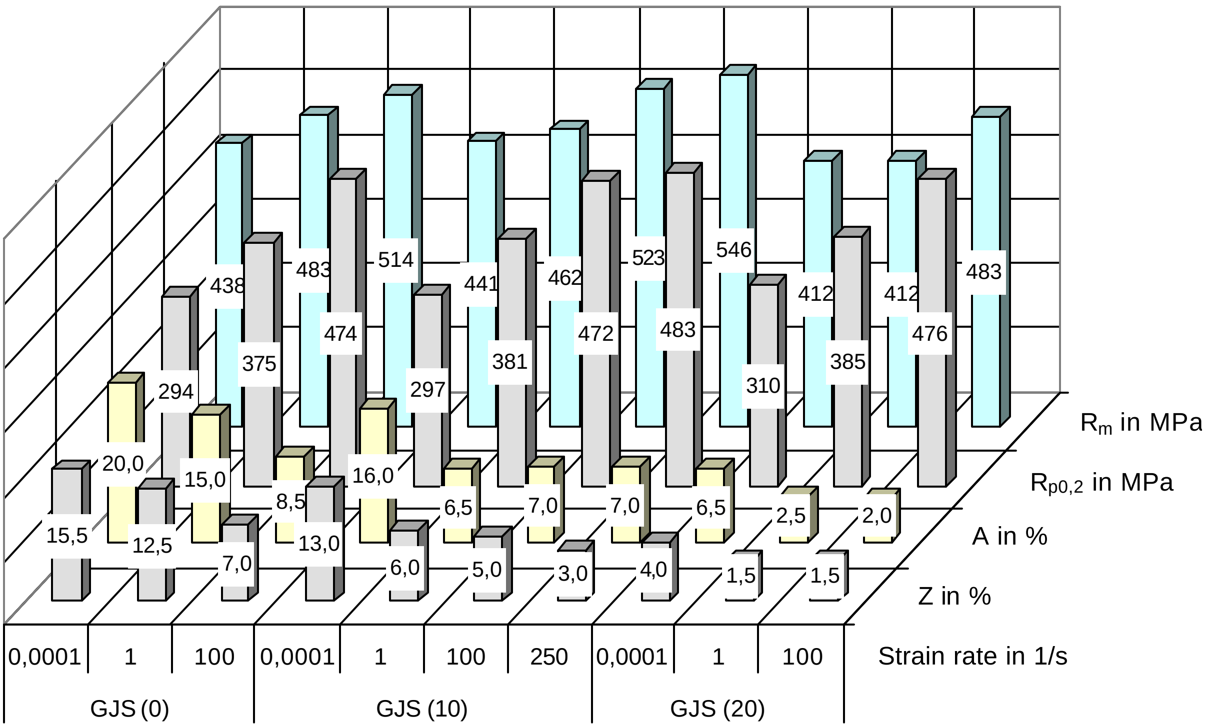

FIGURE 4. Strength and deformation characteristics of GJS (0), GJS (10) and GJS (20) for different strain rates at -40 °C.

As already mentioned above, flow curves are important input data for numerical simulations within the assessment of structural integrity. Therefore, selected results of the true stress-strain behaviour are briefly outlined in the following to monitor the basic findings.

Fig. 5 shows the influence of pearlite content on the true stress-strain behaviour of DCI for two selected strain rates at ambient temperature. For clarity, fit curves have been added to the 100/s strain rate data. Independent from strain rate, the flow behaviour is not significantly influenced by the pearlite content in the investigated range and there are narrow bounds for the three materials investigated. Nevertheless, the curves of GJS (20) do show slightly higher strength levels within these bounds. The increase of pearlite content up to 20 % leads to remarkably shorter flow curves i.e. the UTS values are reached at lower uniform elongation values and the elongation at rupture values decrease too. Although the flow curves as well as the technical stress-strain curves (not shown here graphically) of GJS (20) lie on a slightly higher level than with GJS (0) and GJS (10), these curves are terminated fairly early by specimen rupture due to limited ductility budget. Therefore, the strength characteristics of GJS (20) do not reach the level of GJS (0) and GJS (10) as one probably would have expected.

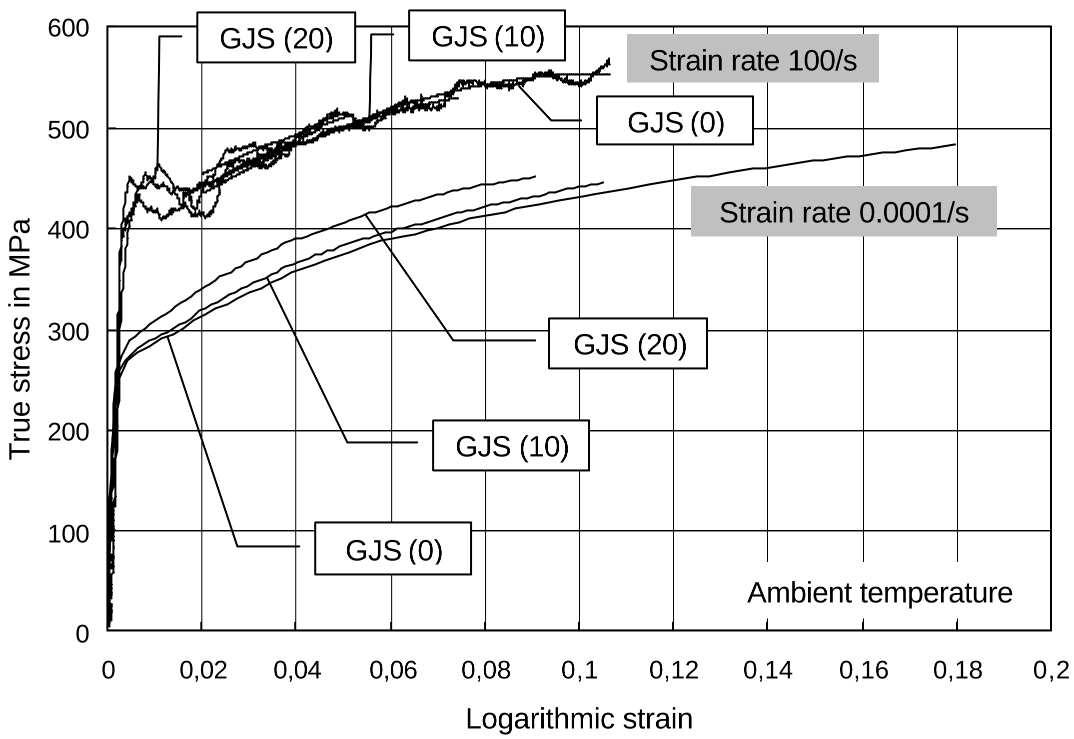

FIGURE 5. Influence of pearlite content on the true stress-strain behaviour of DCI at two selected strain rates, ambient temperature.

Fig. 6 mirrors the basic effect of temperature on the true stress-strain behaviour. Independent from strain rate, the flow curves are shifted towards approximately 10 % higher strength levels by decreasing the test temperature from ambient temperature to -40 °C.

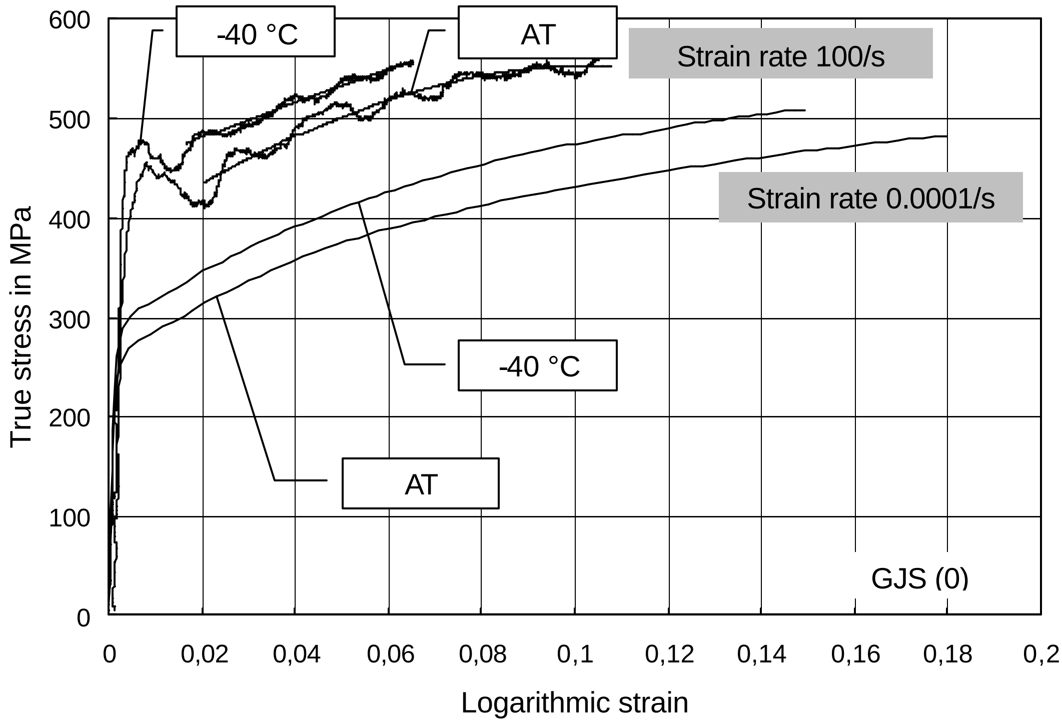

FIGURE 6. Influence of temperature on the true stress-strain behaviour of DCI at two selected strain rates, GJS (0), AT – ambient temperature.

The influence of strain rate on the stress-strain behaviour was investigated in a range of strain rates of more than six orders of magnitude. As an example, Fig. 7 (see next page) shows flow curves of GJS (10) at ambient temperature and different strain rates. An increase in strain rate causes a significant and nearly parallel shift of the flow curves towards higher strength levels. Comparable results are basically found with GJS (0) and GJS (20) as well as the –40 °C test condition. If both influences act together, an increase in strain rate up to the moderate level of 100/s as well as a decrease in test temperature down to –40 °C, only a very limited ductility budget remains especially with GJS (20), Fig. 4.

Summary and Outlook

An optimized testing method for dynamic tensile tests on DCI materials had been established and practiced. The results of systematic investigations on the mechanical material properties of DCI under dynamic loading conditions were reported and discussed in terms of dynamic strength and deformation characteristics as well as dynamic true stress-strain curves. The strain rate influence was significant and found to be clearly stronger than the moderate temperature influence or the effect of pearlite contents of the DCI matrix. Ongoing and further investigations deal with the extension of the strain rate range, a more detailed approach to the microstructure-property correlation and the modeling of the temperature and strain rate dependent mechanical behaviour of DCI.

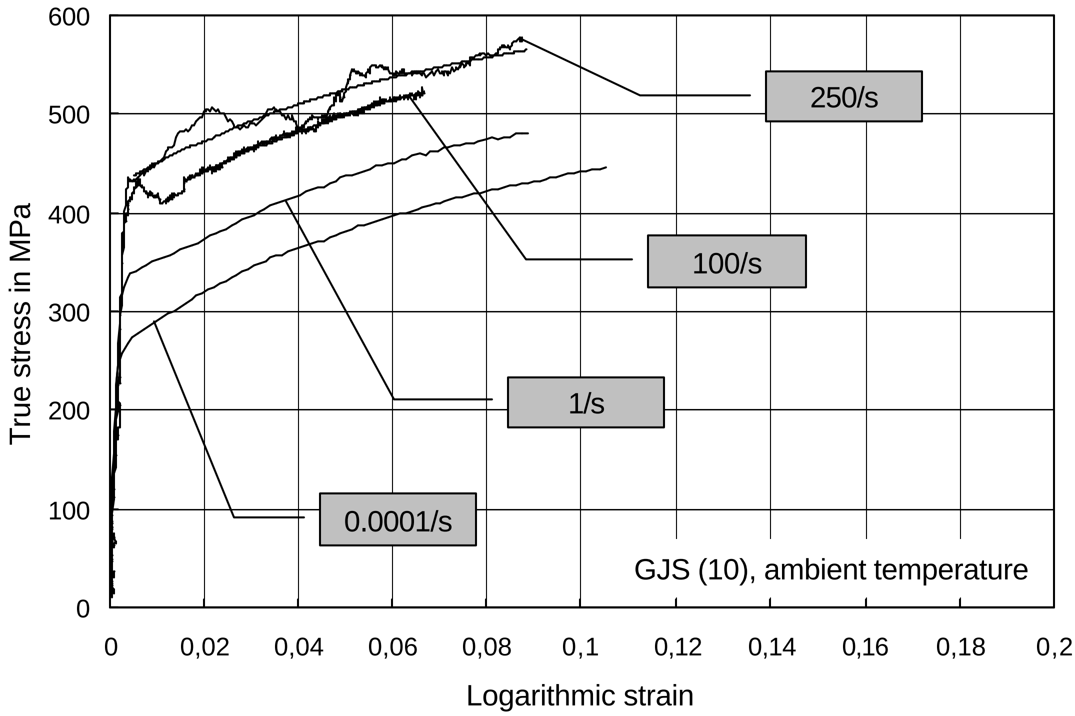

FIGURE 7. Influence of strain rate on the true stress-strain behaviour of DCI, GJS (10), ambient temperature.

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