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Spall strength of polycarbonate at a temperature of 20−185°C

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The results of the measurements of spall strength of polycarbonate at a maximum compression stress of 0.6 GPa in the initial temperature range of 20−185°C are presented. It has been found a significant decrease in the spall strength when the polycarbonate reached the glass transition temperature. The strain rates in the plastic compression wave are determined depending on the maximum stress under single and stepwise shock compression. The dependences of the shock wave velocity Us — mass velocity up in the range of maximum shock compression stresses up to 0.8 GPa at different temperatures are constructed.

Keywords: Polycarbonate, shock waves, deformation, temperature, spall strength, shock adiabate.

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Introduction

Polycarbonate is one of the most durable polymer materials which is widely used as a structural material in aviation and space technology, mechanical engineering and many other industries. The combination of such properties as low density, transparency, and high mechanical strength make it unique. The study of the properties of polymers and development of adequate models of their behavior at high deformation rates over a wide temperature range is quite relevant due to the possibility of using polycarbonate products and structures in the operational environment and under the pulsed load conditions as well [1–5].

The Hugoniot of polycarbonate was studied in a wide range of pressures [6–8]. In addition, the paper [6] studied the shock of the intensity of shock compression on its resistance to tensile stresses and it was found that the spall strength of polycarbonate initially does not change with an increase in the impact velocity to 1 km/s and equals to 0.195 GPa, however, the material softens at a peak stress of 1.6−1.9 GPa and the strength decreases to 0.153 GPa. The tensile strength of polycarbonate was also studied in [9] with an exposure of a sample to a laser pulse when the deformation rate was $10^7\,\mathrm{s}^{-1}$. A hydrodynamic model was developed based on the experimental data that neglects viscoelastic effects, and the maximum value of the spall strength was estimated, which amounted to 1.3 GPa for these loading conditions.

Due to insufficient experimental data, special attention should be paid to the impact of temperature on the strength characteristics of polycarbonate at a temperature close to the glass transition temperature of the polymer, as well as the process of transition from a crystalline state to a glassy one. This study was conducted for polymethylmethacrylate [10] — Hugoniots were constructed, and its resistance to compressive and tensile stresses at various temperatures was studied. It was shown that the material retains a small resistance only to tensile stresses when the glass transition temperature is exceeded. The authors explain this effect by the role of bulk viscosity that increases with temperature in comparison with shear viscosity in the fracture resistance.

The purpose of this work is to study the effect of temperature on the shock compressibility and strength characteristics of polycarbonate in the temperature range from 20 to 185°C, including its transition to a glassy state.

1. Material and experimental setup

The experiments were conducted using BORREX polycarbonate samples with a thickness of 1.8 ± 0.1 mm and 3.3 ± 0.1 mm, with a diameter of 50 mm, cut from one sheet of the appropriate thickness. The initial temperature of the samples ranged from 20 to 185°C. Polycarbonate glass transition, determined by the method of differential scanning calorimetry [11], occurs in the temperature range 142−152°C. Polycarbonate density measured by hydrostatic weighing amounted to $\rho_0 = 1.194\,\mathrm{g/cm^3}$, the measured longitudinal velocity of sound is $c_l = 2.242$ km/s.

Shock-wave loading of the studied samples was carried out using a pneumatic barrel unit with a diameter of 50 mm. The spall strength was measured by loading the studied samples with a thickness of 1.8mm with an aluminum impactor with a thickness of 0.7 mm, accelerated to a speed of 360 ± 10 m/s. The test set up for testing the spall strength of polycarbonate is shown in Fig. 1, *a*. To prevent deflection of the impactor during acceleration, the latter was glued onto a polymethylmethacrylate (PMMA) substrate with a thickness of 5 mm placed on a hollow duralumin

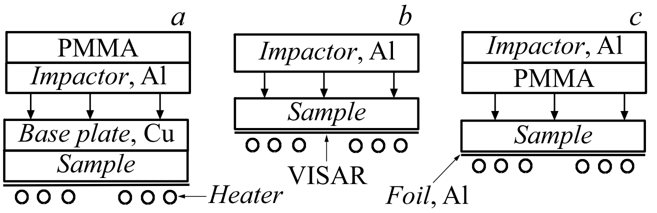

Figure 1. Scheme of experiments on impact loading of polycarbonate samples at room and elevated temperatures: *a* — measurement of the spall strength , *b* — development of relationships $U_S - u_p$, *c* — stepwise loading.

cylinder. The aluminum impactor decelerates when it loads polycarbonate having a higher dynamic impedance with the generation of a stepwise unloading wave in the sample. A stepwise unloading prevents a spall fracture. The sample was placed on a copper base plate with a thickness of 3.5 mm. When an aluminum impactor collides with a copper base plate that has a higher dynamic impedance, the impactor bounces off the base plate, and an unloading wave propagates into the base plate. The presence of a PMMA substrate leads to incomplete, but sufficient for rebound unloading of the impactor and the generation of a rarefaction wave in the base plate, which then propagates into the polycarbonate sample, with an amplitude sufficient to form a spall fracture. The choice of the base plate material is determined by the high dynamic impedance in comparison with the impactor material and the low dynamic elastic limit. The maximum compression stress in polycarbonate with such a test setup was 0.56 GPa. Before the experiment, the receiving chamber and the barrel of the pneumatic installation were vacuumized.

A second series of experiments was performed for development of the relationship of the impact wave velocity U_S and the mass velocity u_p (polycarbonate Hugoniot) by loading samples with a thickness of 3.3 mm with an aluminum impactor with a thickness of 4 mm, as shown in Fig. 1, *b*. The velocities of the impactors were 130 ± 10, 280 ± 10 and 316 ± 10 m/s, which corresponds to the maximum compression stresses of 0.23, 0.59 and 0.74 GPa at room temperature. The range of applied pressures in this series of experiments includes the pressures at which the spall strength measurements were carried out.

The third series of experiments for a stepwise shock compression of samples was carried out to clarify the measured relationships $U_S - u_p$. Stepwise impact compression of samples with a thickness of 3.3 mm was performed using a impactor composed of an aluminum plate with a thickness of 7 mm and from the sample side — PMMA gaskets with a thickness of 1.2±0.1 mm. The composite impactor and the loading arrangement are shown in Fig. 1, *c*. The collision of the impactor with the sample in the plexiglass gasket between the sample and the aluminum plate produced multiple re-reflections of the impact wave. The thickness of the gasket was chosen, on the one hand, so that the difference in arrival time between the first and second compression waves was sufficient to establish the constancy of the free surface velocity after the first wave reached the surface of the sample, on the other hand, so that the result of reflection of the first compression wave from the free surface could not lead to significant distortions of the second wave. The velocity of the composite impactor in these experiments was 338 ± 10 m/s.

The free surface velocity of the samples was recorded as a function of time $u_{fs}(t)$ in all experiments during loading using a VISAR [12] with a resolution of ~ 1 ns. Aluminum foil with a thickness of $7\,\mu$m was used as a reflector of probing laser radiation. The copper base plate and the reflective foil were glued to the sample using a high-temperature epoxy resin PEO 90-K, the upper limit of the operating range of which is 200°C. The samples were heated using a ceramic heater with a nichrome spiral, which was placed at the back surface of the sample, as shown in Fig. 1. The temperature was controlled by two chromel-alumel thermocouples. One thermocouple was glued into the sample at a distance of $\sim 6-7$ mm from the place of recording of the free surface velocity, the second thermocouple was attached from the end of the sample or from the end of the copper base plate in shear strength measurement tests. The difference between the thermocouple data did not exceed 7−8°C. The use of two thermocouples made it possible to definitively control the beginning of the glass transition process in polycarbonate: when the glass transition temperature is reached, the heating rate decreases. The average heating rate of the samples was $\sim 0.1°$/s.

The velocity of the shock wave was measured as the difference between the time of the shock wave's arrival to the free surface and the moment of impact recorded using electrocontact sensors. Four sensors located at a distance of 19 mm from the center of the sample were used to increase the accuracy of measurements and to record the impactor bias. The sensors were also glued using high-temperature epoxy resin and sanded in the same plane with the back surface of the sample.

2. Measurement results

2.1. Analysis of wave profiles

Figure 2 shows free surface velocity profiles of polycarbonate samples with a thickness of 1.8mm, obtained in the initial temperature range from 20 to 185°C. The arrival of the plastic compression wave to the surface is recorded on the profiles. There were no signs of an elastic-plastic transition at the compression wave front. After the reflection of the impact wave from the free surface in the form of a rarefaction wave and the interaction of the latter with the incident rarefaction wave coming from the back of the impactor, tensile stresses are produced inside the sample, leading to its spall failure. Next, the arrival of the spall pulse to the surface is recorded in the form of a second velocity rise associated with its propagation to the free surface of the sample.

The maximum of the free surface velocity in the experiment at room temperature (Fig. 2) was ~ 330 m/s. The calculated maximum of the free surface velocity using the known polycarbonate Hugoniot [7,8] without taking into account the attenuation of the impact wave during its propagation through the sample should be $\sim 390{-}400$ m/s. An increase of the of the free surface velocity to 350 m/s is recorded with an increase of the temperature to the glass transition temperature (141°C). This effect is caused by the fact that with an increase in temperature there is a decrease in the velocity of the shock wave and the velocity of propagation of the frontal part of the unloading, the attenuation of the full compression pulse slows down with an increase in the temperature of the sample, and the surface velocity slightly increases. The maximum free surface velocity drops significantly and is recorded at the level of 302–312 m/s in the temperature range from 141 to 185°C, i.e. in the glass transition region and above. The maximum of the free surface velocity decreases probably due to an increase in the velocity of the unloading wave. Irregular oscillations occur on the wave profiles, and their reproducibility degrades at sample temperatures above the glass transition start temperature. This indicates the processes associated with the restructuring of the internal structure in polycarbonate and, possibly, with the growth of pores in the softened material. A significant variation in the maximum of the free surface velocity is observed at the boundary initial temperature of the samples 140°C (glass transition process temperature). This is due to the fact that the glass transition process, unlike melting or crystallization, occurs continuously and is a relaxation process. „Defrosting of“ segmental mobility in the sample occurs unevenly, so the values of the maximum surface velocity recorded in this range differ even at the same temperature [13].

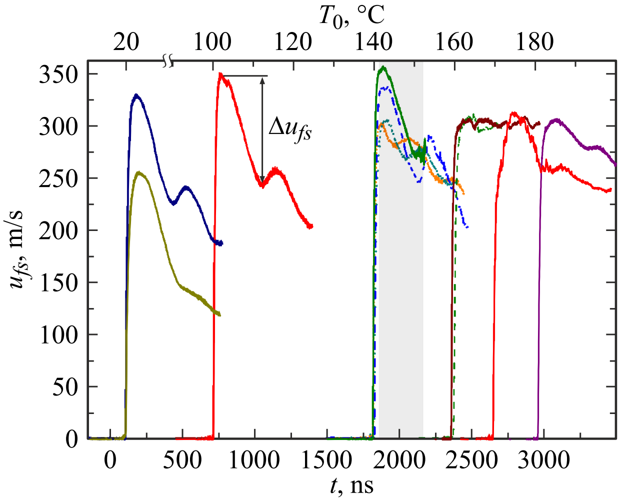

Figure 2. Free surface velocity profiles of polycarbonate samples with a thickness of 1.8 mm when impacted by an aluminum impactor with a thickness of 0.7 mm at a speed of 360 ± 10 m/s in the temperature range from 20 to 185°C. The shaded temperature range corresponds to the glass transition range of polycarbonate.

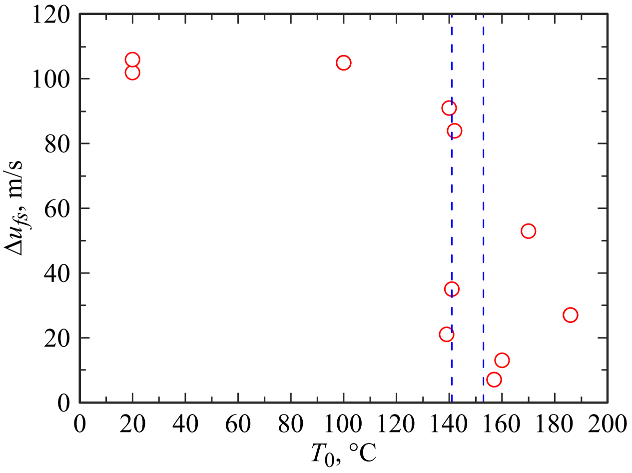

Figure 3. The relationship of the value of Δ_{ufs} polycarbonate and the temperature; the stroke shows the temperatures of the beginning and end of the glass transition.

2.2. Spall strength of polycarbonate

The velocity pullback is the difference between the maximum value of the free surface velocity and the minimum value in the unloading wave Δu_{fs} (Fig. 2) which is proportional to the shear strength of the material [14]. Figure 3 shows the relationship of Δu_{fs} and the initial temperature of the sample. It can be seen that before the samples reach the glass transition temperature, the velocity pullback practically does not change, and with the beginning of the glass transition process it drops sharply. A slight increase of Δu_{fs} is observed at temperatures above the glass transition termination temperature. It can be noted that at room temperature (Fig. 2) the intensity of shock compression (0.42 and 0.56 GPa) does not affect the magnitude of the velocity pullback in the unloading wave.

The magnitude of the tensile maximum stresses or the spall strength was calculated in a linear (acoustic) approximation based on the measured velocity pullback Δu_{fs} using the ratio $\sigma_{sp} = 1/2\rho_0 c_b(\Delta u_{fs} + \delta)$ [15], where ρ_0 is the initial density, c_b is the bulk velocity of sound, δ is the correction for distortion of the velocity profile due to the difference in the velocities of the elastic front of the spall pulse and the velocity of the plastic part of the incident unloading wave in front of it. The correction value of δ was assumed to be zero for calculation of the spall strength due to the absence of the elastic properties of polycarbonate under shock compression. Data from [16] were used to calculate the density change with the increase of the temperature.

Fig. 4 shows the obtained values of the spall strength of polycarbonate in the temperature range of 20–185°C. The calculated value of the bulk speed of sound obtained

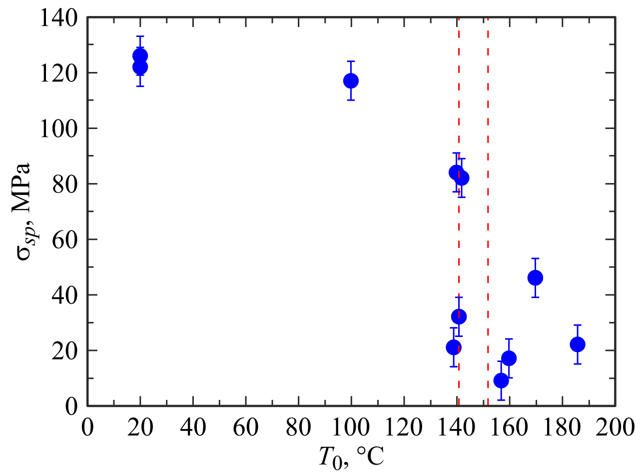

Figure 4. Relationship of the spall strength of polycarbonate and the initial temperature.

from the stepwise loading experiment at 170°C was used to calculate the spall strength at 160 and 185°C and the procedure for obtaining it is shown below. The figure shows that an increase in the temperature of the samples to the glass transition temperature leads to a gradual decrease in the value of the spall strength. The beginning of glass transition and further heating leads to a relatively sharp drop in all parameters (density, velocity Δu_{fs}, bulk speed of sound), and, as a consequence, a decrease in the value of the spall strength of polycarbonate. This can be explained by the nature of the glass transition process, since the mobility of the polymer chains increases with the energy obtained and its softening "occurs" and at the same time its strength decreases. The strain rate [17] estimated by the decrease in the velocity of the sample surface in the unloading wave before the spall fracture practically does not depend on the initial temperature of the sample and is in the range $(0.7-1.2)\cdot 10^5\,\mathrm{s}^{-1}$. The value of the polycarbonate spall strength of 0.195 GPa was obtained in the study [6] at close strain rates which is significantly higher than the value measured in this work, however, the samples studied there have other characteristics (density, longitudinal velocity of sound), which may be related to the manufacturing technology.

2.3. Determination of impact compressibility of polycarbonate at elevated temperatures

The value of the bulk velocity of sound c_b was assumed to be equal to c_0 depending on the shock wave velocity U_s on the particle velocity u_p, $U_s = c_0 + bu_p$, where the coefficient b is determined by the slope of the linear relationship. A second series of experiments was carried out to determine the values of the bulk velocity of sound at room and elevated temperatures where the shock compressibility of polycarbonate was measured as a relationship of the shock velocity and the particle velocity at room and elevated temperatures. The particle velocity u_p was defined as $u_p = u_{\max}/2$, where $u_{\max}$ — the maximum value of the free surface velocity (Fig. 5). The shock wave velocity was calculated using the formula $U_S = h_s/t_0$, where h_s is the thickness of the sample, and t_0 is the difference between the time of the arrival of shock to the free surface and the time recorded using electrocontact sensors, which are triggered when the aluminum plate hits the back surface of the sample. Since two pairs of sensors were used in the experiments, the time t_0 was determined as an arithmetic mean.

Figure 5 shows the profiles of the free surface velocity obtained when loading polycarbonate samples with a thickness of 3.3mm with an aluminum impactor with a thickness of 4mm, accelerated to speeds of 130 ± 10, 280 ± 10 and 316 ± 10 m/s. The free surface velocity profiles were measured in the initial temperature range of the samples 20−170°C. A decrease in the rise time in the shock wave front is observed with a increase in temperature which indicates a decrease in the viscosity of the material under study. An increase in the free surface velocity is recorded at one shock velocity with an increase in the initial temperature of the sample which indicates a decrease in the dynamic impedance of polycarbonate with an increase in temperature.

Figure 6 summarizes the obtained relationships $Us-up$ for polycarbonate at initial temperatures of 20, 100 and 138°C. It can be seen that at room temperature, the resulting Hugoniot is well aligned well with the data given in [7,8]. With temperature increase, the obtained relationships $Us-up$ are lower than the Hugoniots at a lower temperature. The impact of the initial temperature of the samples on the coefficient b was not detected.

The obtained cb value from the polycarbonate impact adiabat at room temperature ($c_b = 1.955$ km/s) is lower than the measured longitudinal velocity of sound

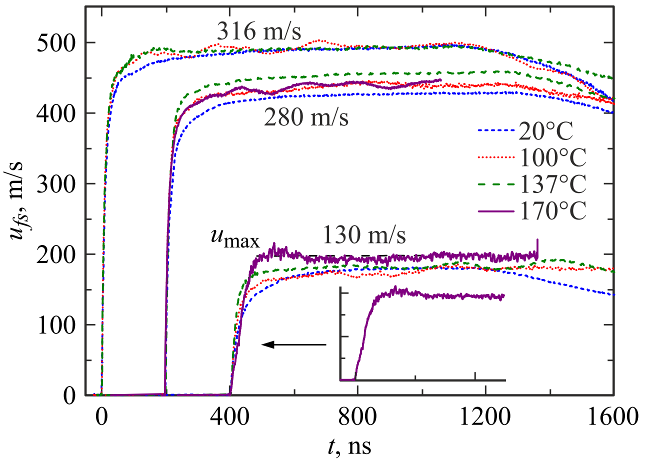

Figure 5. Profiles of the free surface velocity of polycarbonate samples with a thickness of 3.3 mm when struck by an aluminum plate with a thickness of 4 mm with velocities of 130−316 m/s at temperatures of 20−170°C.

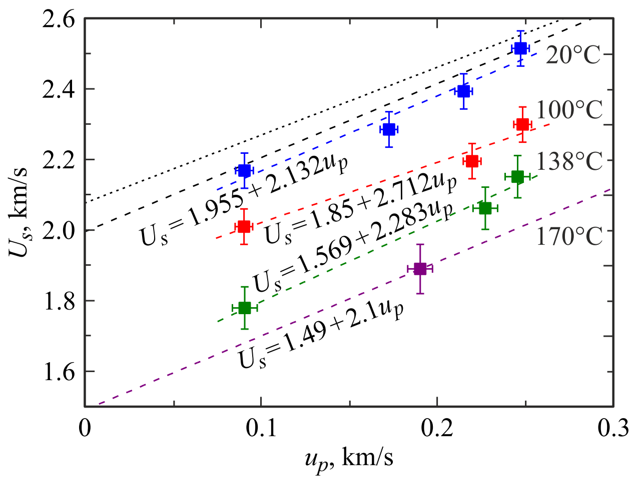

Figure 6. Results of measurements of polycarbonate Hugoniot in the temperature range 20−170°C. The linear relationship at 170°C is obtained as a result of calculations. Stroke — study data [7], dots — study data [8].

($c_l = 2.242$ km/s). The velocity of the shock wave is equal to c_l at a mass velocity of 0.140 km/s (Fig. 6), i.e. splitting of the shock wave with the release of an elastic precursor above this speed is impossible. The splitting of the shock wave with the release of an elastic precursor propagating at the longitudinal speed of sound was not recorded at a particle velocity of 0.09 km/s (Fig. 5). Apparently, the yield strength of polycarbonate under impact loading is very small. An elastic precursor in experiments on impact loading of polycarbonate at close particle velocities was also not registered in the work of [6]. In the experiment with polycarbonate at 170°C and an shock velocity of 130 m/s, a feature of the compression wave wavefront is recorded in the form of the formation of a two-wave configuration (insert in Fig. 5), possibly related to the release of an elastic precursor, which, in turn, may be caused by the transition of polycarbonate to a highly elastic state under these conditions [13]. A similar feature was observed in experiments with PMMA at initial temperatures exceeding the glass transition temperature [10].

Experiments to determine the shock compressibility with the initial temperature of the samples 170°C and higher contained a large error in measuring the shock wave velocity, which may be attributable to a change in the position of the electrocontact sensors during sample softening. For this reason, an additional series of experiments on stepwise compression of polycarbonate samples was carried out, during which it was supposed to estimate the time of the arrival of the second wave to a free surface. Fig. 7 shows the profiles of the free surface velocity of polycarbonate samples loaded with a composite impactor made of PMMA and aluminum accelerated to a speed of 338 ± 10 m/s (Fig. 1, *c*). The experiments were carried out at room and elevated to 100, 137 and 170°C temperatures. An increase in the initial temperature, as well as in experiments on measuring shock compressibility, led to an increase in the free surface velocity. The change of the time of exit of the second wave to the surface of the sample turned out to be more significant — the arrival time of the second compression wave relative to the first at 20°C was 500 ns, and it was 360 ns at 170°C. The analysis of the propagation of the first and second compression waves showed that the use of the obtained relationships *Us*−*up* at 20, 100 and 137°C in the calculation is well aligned with the results of measurements of the velocity profiles of the free surface. The times of arrival of the second plastic compression to the free surface were determined with good accuracy when constructing *t*−*x* diagrams of impact-wave interactions. The measured Hugoniot at 170°C prevented from determining the exact time of the second compression wave's arrival to the free surface. Therefore, to construct a Hugoniot at 170°C, the inverse problem was solved. Using the data obtained in the stepwise compression experiment, the relationship U_{S-u_p} was calculated as $U_s = 1.49 + 2.1u_p$. The later output of

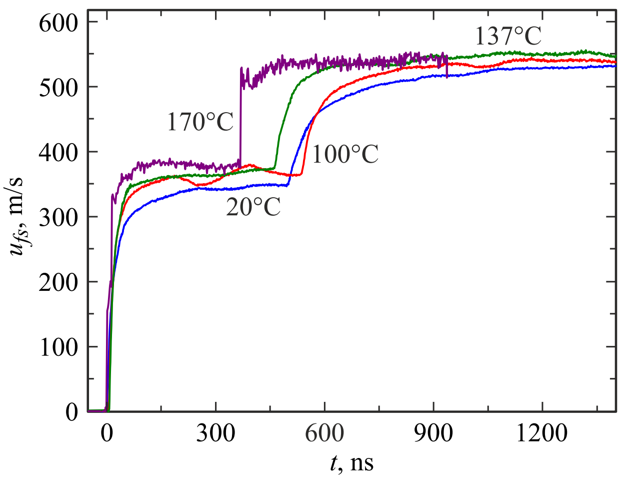

Figure 7. Profiles of the free surface velosity of polycarbonate samples when struck by a composite impactor at a speed of 338 ± 10 m/s at temperatures of 20−170°C.

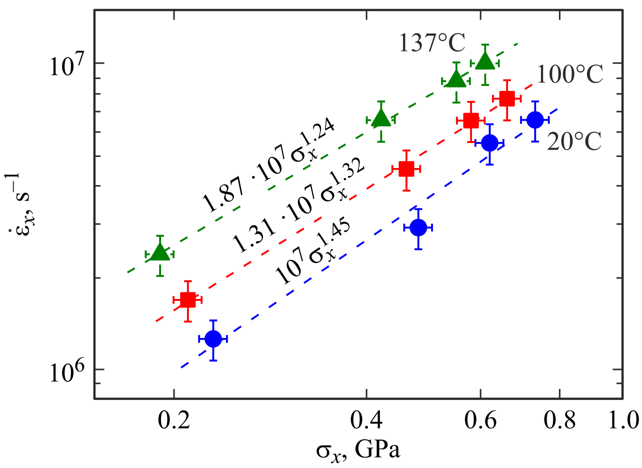

Figure 8. The relationship of the strain rate in a plastic wave and the maximum compression stress.

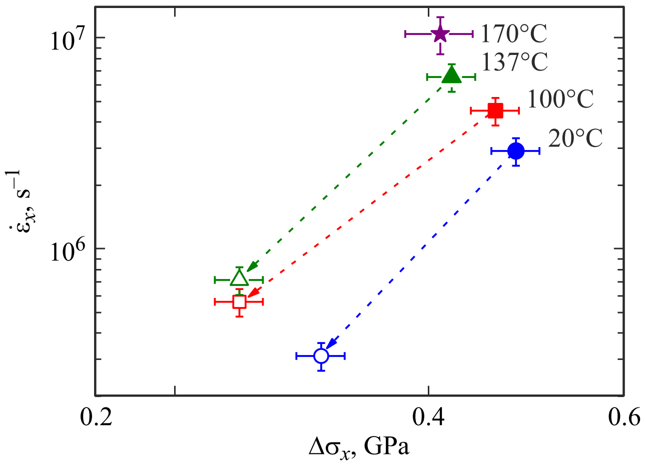

Figure 9. Compression rates depending on the difference in principal stresses in a plastic impact wave. The arrows connect the parameters of the first and second plastic waves of the same experiment.

the second compression wave in the experiment at 100°C compared with the experiment at 20°C is associated with a slight difference in the thickness of the impactor and the sample.

The maximum compression rate of first and second plastic waves and the maximum compression stresses when the shock waves arrived to the free surface were determined using the measured free surface velocity profiles, shown in Fig. 5 and 7. The compression rate was defined as $\dot{\varepsilon}_x = \dot{u}_{fs}/2U_S$, where $\dot{u}_{fs}$ is the maximum acceleration of the surface in a plastic wave, U_S is the velocity of the plastic impact wave. The maximum shock compression stress was defined as $\sigma_x = \rho_0 U_s u_p$. Figure 8 shows the relationships of the deformation rate on the maximum compression stress obtained in experiments to determine the particle velocity and in experiments on stepwise loading of samples at the output of the first wave. As can be seen in the figure, the compression rate changes in a similar way with an increase in the maximum compression stress in the impact wave in the studied range of initial temperatures and can be described by a power-law relationship $\dot{\varepsilon}_x = A(\sigma_{peak}/\sigma_0)^\beta$ ($\sigma_0 = 1$ GPa). With temperature increase in the range of maximum compression stresses up to 1 GPa values of the power factor β decrease from 1.45 at 20°C to 1.24 at 137°C. In the studied compression stress range, the strain rate at 137°C is twice as high as at 20°C, which indicates a decrease in the viscosity of the material as it approaches the glass transition temperature. This difference slightly decreases with an increase in the maximum shock compression stress.

Figure 9 compares the results of measuring the strain rate in the first and second plastic impact waves at different temperatures. The comparison is made depending on the increment of the compression stress in the plastic wave. The solid points show the values of the strain rate for the first plastic wave, the values for the empty points were taken as the difference between the compression stresses for the second and the first plastic shock waves. The points describing the second plastic waves are located below the relationships for the first waves. The rate of deformation in the second plastic wave also increases with an increase in temperature.

Conclusion

Experiments were carried out to record complete wave profiles using a VISAR of polycarbonate samples under impact compression up to 0.8 GPa in the temperature range $20-185^\circ$C. The values of the spall strength of polycarbonate were determined using the analysis of wave profiles depending on temperature at a maximum compression stress of 0.6 GPa. It is found that the transition of polycarbonate from a glassy to a highly elastic state affects the decrease in resistance to tensile stresses more strongly than the usual temperature increase. The partivle velocity and the shock wave velocity were measured at the temperature of the beginning of glass transition and in a highly elastic state for calculation of the spall strength of the polycarbonate. Polycarbonate Hugoniots are constructed in the range of maximum impact compression stresses up to 0.8 GPa based on the experimental data obtained. It is shown that the value of the bulk velocity of sound — the first term of the linear relationship $U_S = c_0 + bu_p$ — decreases with an increase in the initial temperature and the coefficient b slightly changes. There were no signs of elastic-plastic behavior of polycarbonate under shock compression. The strain rates in a plastic wave are determined depending on the maximum stress during single and stepwise impact compression. Maximum compression strain rates are realized at elevated temperatures.

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Conflict of interest

The authors declare that they have no conflict of interest.

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