Glass-forming ability versus stability of silicate glasses.
I. Experimental test

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Abstract

We recently proposed that the Hrubý parameter of glass stability \((K_H)\) could be used to estimate the vitrification ability of glasses that nucleate internally. In that research, we used calculated critical cooling rates \((q_{cr})\) for four glasses. In this article, we report on our measurements of the critical cooling rates of seven glasses: \(\text{Li}_2\text{O} \cdot 2\text{SiO}_2\), \(\text{Na}_2\text{O} \cdot \text{CaO} \cdot 3\text{SiO}_2\), \(2\text{Na}_2\text{O} \cdot \text{CaO} \cdot 3\text{SiO}_2\), \(\text{BaO} \cdot 2\text{SiO}_2\), \(\text{Li}_2\text{O} \cdot 2\text{SiO}_2 \cdot \text{OH}\), \(2\text{BaO} \cdot \text{TiO}_2 \cdot 2\text{SiO}_2\) and \(0.44\text{Na}_2\text{O} \cdot 0.56\text{SiO}_2\). We modified and used a method put forward by Colmenero and Barandiarán (CB) to estimate the \(q_{cr}\). The experiments were accomplished in two steps. In the first, monolithic pieces of each glass, obtained by splat cooling the melts, were heated in a Pt crucible, at the same heating rate, to estimate the glass transition, crystallization and melting temperatures. We then calculated the Hrubý parameter, \(K_H\), based on these quantities. In the second step, the same samples were melted, then cooled at different rates and the crystallization temperatures observed were used to estimate \(q_{cr}\). In another set of tests, we used \(\text{Al}_2\text{O}_3\) and graphite crucibles, repeating the same procedures for the \(\text{LS}_2\) glass. The effect of the crucible’s material (Pt, C and \(\text{Al}_2\text{O}_3\)) on the crystallization temperatures is discussed. A relationship between \(q_{cr}\) and \(K_H\) is experimentally demonstrated.

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1.Introduction

All materials are vitrifiable if the cooling rates used to solidify their melts are fast enough to prevent the occurrence of a detectable fraction of crystals, usually assumed to lie between \(10^{-2}\) and \(10^{-6}\). The cooling rate to produce that minimum crystallized fraction is denominated the critical cooling rate, \(q_{cr}\). However, it is quite difficult to accurately measure the \(q_{cr}\).

We recently observed that the Hrubý parameter \((K_H)\), which easily measures glass stability (GS) against devitrification on heating, can be used to estimate the glass-forming ability (GFA) on cooling [1]. In that research, the calculated critical cooling rates \((q'_{cr})\) of four glasses were compared with \(K_H\), demonstrating a correlation. However,
our results contradicted Weinberg’s [2] suggestion, which affirmed that, although GFA and GS are related concepts, they are ill-related quantities. Additionally, because we had analyzed only four systems in Ref. [1], in this research we test another three glasses to generalize (or not) our previous findings. Furthermore, we use an experimental rather than calculated \( q_{cr} \).

1.1. Literature review

Twenty years ago, Colmenero and Barandiarán [3] proposed an experimental method to measure critical cooling rates using thermal analysis techniques (DSC or DTA). This method will be dubbed the CB method. As far as we know, only a few researchers have tested this method to estimate \( q_{cr} \). We will briefly review some of them in the following paragraphs.

Wichard and Day [4] determined the critical cooling rates for five compositions of the Ga2O3–CaO system. Using a Pt–10% Rh thermocouple, they determined \( q_{cr} \) by repeated cooling and heating experiments. Each composition was melted between 150 and 250 °C above its respective liquidus and cooled at least 30 times at various rates. As they expected, eutectic compositions displayed a greater tendency to vitrify.

Another interesting study was conducted by Huang et al. [5]. Using a glass of nominal composition 40Li2O–60SiO2 mole%, they showed that \( q_{cr} \) increases with increasing Pt and Au additions, but Pt has a stronger effect than Au. They used two methods for \( q_{cr} \) measurements, the first being the one used by Wichard and Day [4], and the second the one proposed by Colmenero and Barandiarán [3]. An excellent agreement was found between these values, even when different amounts of Pt and Au were used.

Finally, Ray and Day [6] measured the critical cooling rates for five compositions of the BaO–TiO2–SiO2 system, suggesting that the tendency for glass formation increases with increasing silica content, as expected.

In the present paper, we report on our modification of the CB method [3] and determination of the critical cooling rates of seven ‘model’ glasses (that show internal nucleation) having almost stoichiometric compositions: \( \text{Li}_2\text{O} \cdot 2\text{SiO}_2 \) (LS2), \( \text{Na}_2\text{O} \cdot 2\text{CaO} \cdot 3\text{SiO}_2 \) (NC2S3), \( 2\text{Na}_2\text{O} \cdot \text{CaO} \cdot 3\text{SiO}_2 \) (N2CS3), \( \text{BaO} \cdot 2\text{SiO}_2 \) (BS2), \( \text{Li}_2\text{O} \cdot 2\text{SiO}_2 \) with 0.2% mole OH (LS2OH), \( 2\text{BaO} \cdot \text{TiO}_2 \cdot 2\text{SiO}_2 \) (B2TS2) and 0.44Na2O·0.56SiO2 (NS).

Our experiments were performed in two steps. In the first, monolithic pieces of each glass were heated in Pt, alumina or graphite crucibles (at the same heating rate) to estimate the Hruby parameter and test its sensitivity to the crucible material. Then, the same samples were melted and cooled at variable cooling rates (from 1 to 50 °C/min) and their crystallization temperatures on cooling used to estimate \( q_{cr} \) by the modified CB method. An important effect of the crucible material on the crystallization temperatures of these glasses was detected. We confirm the relationship between \( q_{cr} \) and \( K_{H} \) proposed in Ref. [1] and discuss the relevance of these findings to the vitrification of reluctant glass-forming systems.

The following sections describe and discuss the relevant theory, the experimental methods used and the results of this research.

2. Theory

2.1. Methods to determine \( q_{cr} \)

Several methods have been proposed to calculate critical cooling rates, \( q_{cr} \). One of the simplest is the so-called nose method, which refers to the nose of a TTT (time–temperature–transformation) diagram. According to this method, there is a corresponding time \( t_n \) for the temperature \( T_n \) of the ‘nose’ of TTT diagrams. Thus, the critical cooling rate for glass formation, \( q_{cr}^n \), is given by

\[
q_{cr}^n = \frac{T_m - T_n}{t_n},
\]

where \( T_m \) is the melting point of the crystal phase or liquidus temperature.

The \( q_{cr} \) determined by the nose method is typically less than an order of magnitude greater than the real \( q_{cr} \) [7]. Thus, the nose method can be used to estimate critical cooling rates and to compare the vitrifiability of different materials [1].
Colmenero and Barandiarán (CB) [3] suggested another experimental method to determine \( q_{cr} \). According to these authors, the cooling rates, which can be measured by differential scanning calorimetry (DSC), are proportional to \( (\Delta T_c^s)^{-2} \). The expression proposed in [3] is

\[
\ln q = A - \frac{B}{(\Delta T_c^s)^2},
\]

where \( \Delta T_c^s = T_m - T_c^s \), \( T_c^s \) is the peak crystallization temperature on cooling the sample at a cooling rate \( q \). By varying the cooling rate and plotting \( \ln(q) \) versus \( 1/(\Delta T_c^s)^2 \), if the equation is correct, one should obtain a straight line. The constant \( A \) can be determined from the intercept of the straight line and \( B \) can be obtained from the curve slope. According to [3], when \( \Delta T_c^s \) increases to infinity, no crystallization occurs, leading to

\[
\ln q_{cr} = A.
\]

Therefore, as the value of \( A \) is already known, it is possible to calculate \( q_{cr} \) from Eq. (3a).

One should be aware, however, that \( \Delta T_c^s \) never tends to infinity because it can only vary between \( T_m \) and zero. Therefore, we propose a more realistic expression for \( q_{cr} \), hereinafter called \( q_{cr}^\star \), given by the following equation:

\[
\ln q_{cr} = A - \frac{B}{T_m^2},
\]

2.2. The Hrubý parameter of glass stability

Hrubý proposed that a parameter, \( K_H \), obtained by differential thermal analysis (DTA) or DSC, indicates glass stability against crystallization on heating [8]. The Hrubý parameter is defined by

\[
K_H = \frac{T_{cr}^h - T_g}{T_m^a - T_c^h},
\]

where \( T_{cr}^h, T_g \) and \( T_m^a \) are the onset crystallization temperature (on heating), glass transition and melting temperatures estimated by DSC, respectively. According to Hrubý, the higher the value of \( K_H \) of a certain glass, the higher its stability against crystallization on heating and, presumably, the higher its vitrifiability on cooling [8].

3. Experimental procedures

We carried out several DSC experiments using samples of seven glasses. The \( L_2S, N_2S_3, N_2CS_3 \) and \( B_2S \) glasses were prepared at the Vitreous Materials Laboratory – LaMaV/DEMa-UFSCar, the other two (\( L_2SOH \) and \( NS \)) were synthesized at the Institute of Silicate Chemistry in St Petersburg, Russia and the \( B_2TS_2 \) glass was produced at the Otto-Schott Institute in Jena, Germany. These glasses were melted in Pt crucibles at temperatures approximately \( 50 ^\circ C \) above the respective melting points of the isochemical crystals for a few hours, homogenized and quenched by pressing the liquid between two steel plates.

Monolithic glass pieces weighing approximately \( 10–20 \) mg were placed in a Pt crucible and heated/cooled in the DSC. The same heating rate (20 K/min) was used for all the samples, but the cooling rates varied from 2 to 50 K/min to include the theoretical values of \( q_{cr} \) previously calculated by Cabral et al. [1]. The samples were then reheated to \( 50 ^\circ C \) above the liquidus temperatures and kept there for 5 min to ensure that the material had melted completely before each cooling run.

We performed several experiments for each glass and found different values for \( K_H \) and \( q_{cr} \), which were taken as a measure of the method’s experimental errors. The same procedure was adopted for the other samples and \( \ln(q_{cr}) \) vs. \( K_H \) was plotted for all the glasses.

To evaluate the effect of the crucible’s material on the crystallization temperatures during cooling, \( T_c^s \), three monolithic samples of \( L_2S \) with approximately the same mass were successively heated and cooled in graphite, alumina and platinum crucibles. In all these cases, they were initially heated in a DSC crucible up to \( 40 ^\circ C \) at 5 K/min, kept for 5 min at that temperature and heated at \( 20 \) K/min up to \( 1200 ^\circ C \). They were then cooled at rates of 2, 5, 8, 10 and 20 K/min, using an inert atmosphere of high purity argon. This procedure was repeated several times for each cooling rate. Since all the experimental parameters, such as the samples’ mass, atmosphere, gas flow and heating/cooling rates were constant, the crystallization temperatures obtained during cooling could be compared.
4. Results

The objective of this work was to verify a possible relationship between vitrification ability and stability of glass-forming systems.

Except for the NC$_2$S$_3$ glass, the cooling traces of all the glasses showed several crystallization peaks, a typical phenomenon of surface (heterogeneous) crystallization. Typical cooling curves are shown in Fig. 1. To test the reproducibility of the crystallization temperatures during cooling, $T_c^c$, we successively heated/cooled a monolithic glass sample of LS$_2$ using a platinum crucible. This procedure was repeated from three to five times for each cooling rate. The crystallization temperatures are presented in Table 1. For cooling rates of 10–20 °C/min, the crystallization temperatures $T_c^c$ varied by approximately 50–60 °C! For other cooling rates, variations of about 10–25 °C were observed. These substantial variations are clearly outside the range of instrumental error and demonstrate the sensitivity of heterogeneous crystallization to the presence of solid impurities (from the atmosphere), mechanical vibrations, etc. Upon cooling through the region of high growth rates ($T/T_m \sim 0.9$), any solid impurity or mechanical perturbation can induce fast crystallization of the melt. In addition, it is well known that platinum is an excellent catalyst for crystallization of LS$_2$, NC$_2$S$_3$ and probably of other glasses [5,9]. Since there is surface contact between the melts and the DSC crucibles, these provide a favorable pathway for heterogeneous surface crystallization, leading to irreproducible crystallization temperatures (shown in Table 1). Fortunately, however, this phenomenon does not occur upon heating; thus, the crystallization temperatures are perfectly reproducible. In heating experiments, the glassy samples are (mostly) homogeneously nucleated before they reach a region of substantial growth and then fully crystallize. In order to take heterogeneous crystallization on the cooling path into account, we propose three modifications for the CB method.

Using the same heating/cooling rates and different monolithic samples of each glass, we carried out at least three cooling experiments for each cooling rate. First, when more than one crystallization peak appeared on the cooling trace of a given DSC run, only the peak at the highest temperature (relating to the first phase to crystallize) was considered. We made this choice because, at lower temperatures, the sample already contained crystals. Second, considering all the tests with the same cooling rate, we took the lowest $T_c^c$ peak (among the highest peak of each run) to favor internal (homogeneous) crystallization rather than heterogeneous crystallization. As an example, Fig. 2 shows some traces of a NC$_2$S$_3$ glass in which the crystallization temperatures varied significantly. Third, we calculated $q_{c}$ with the modified Eq. (3b). From the resulting crystallization temperatures for each cooling rate, plots of $\ln(q_{c}) \times 1/(\Delta T_c^c)^2$ were obtained for each glass. Using the respective melting temperatures, the critical cooling rates

![Fig. 1. DSC scans obtained for the LS$_2$ glass with different cooling rates, which are indicated on the right-hand side of the plot.](image)

Table 1
Crystallization temperatures in repeated cooling experiments of the LS$_2$ glass cooled at different rates

<table>
<thead>
<tr>
<th>Cooling rates (°C/min)</th>
<th>$T_c^c$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>983, 984, 979, 988, 985, 989</td>
</tr>
<tr>
<td>5</td>
<td>967, 955, 977, 970, 972, 981</td>
</tr>
<tr>
<td>8</td>
<td>970, 967, 976, 962, 962, 961</td>
</tr>
<tr>
<td>10</td>
<td>963, 973, 959, 945, 912</td>
</tr>
<tr>
<td>20</td>
<td>914, 905, 953, 920, 901, 907</td>
</tr>
</tbody>
</table>

The minimum $T_c^c$ obtained for each cooling rate is italicized.
estimated by Eqs. (3a) and (3b) are presented in Table 2. As an example, Fig. 3 displays the data obtained in one experiment with NC2S3. According to the equation obtained from that figure and Eq. (3b): 
\[ q_{cr} / C^2 = 11 \text{ K/s}. \]

5. Discussion

5.1. Critical cooling rates

The \( q_{cr} \) of Table 2 obtained from the two methods, Eqs. (3a) and (3b), are very close and are qualitatively consistent with our experimental observations in melting and cooling these seven glasses in the laboratory. Additionally, they indicate the same trend of GFA. In other words, LS2 is the easiest glass to make while the Ba2TiSi2O8 melt must be powerfully pressed to avoid crystallization during cooling.

The present CB results for \( q_{cr} \) are about one order of magnitude greater than those previously calculated by the nose method [1]. However, it is known that the nose method overestimates \( q_{cr} \). One could argue that these high \( q_{cr} \) differences result from the fact that the cooling rates used in this work are of the same order of magnitude of \( q_{cr} \), in contrast with Colmenero and Barandiarán's [3] suggestion (the cooling rates employed must be at least two orders of magnitude lower than \( q_{cr} \)).

We should emphasize, however, that the cooling rates used by Wichard and Day [4] and Huang et al. [5] to measure \( q_{cr} \) with the CB technique varied between 50 and 400 °C/s, and 2 and 12 °C/s,
respectively. These values are of the same order of magnitude as the critical cooling rates obtained. Moreover, in the case of the 40Li2O–60SiO2 glass, whose \( q_{cr} \) was measured both directly and by the CB method, the agreement between the CB and experimental value of \( q_{cr} \) was excellent. Therefore, Colmenero and Barandiarán’s suggestion is apparently not required to ensure the accuracy of \( q_{cr} \) estimates.

In our opinion, the fact that the critical cooling rates calculated by the nose method are lower than those estimated by the CB method is due to heterogeneous nucleation of the melts on the Pt crucible walls, as discussed below.

The \( K_H \) values obtained for each glass are reported in Table 3. The typical measurement errors were about 5–40%. Fig. 4 was plotted from the critical cooling rates evaluated through Eq. (3b), \( q_{cr} \), and the \( K_H \) values obtained for each glass. This figure comprises a 2 o.m. range of \( q_{cr} \), \( 0.5 < q_{cr} < 50 \), and indicates that a relationship between \( q_{cr} \) and \( K_H \) exists: the higher the \( K_H \) the lower the \( q_{cr} \).

These results are contradictory to those of Ref. [2]. On the other hand, in a forthcoming paper, Avramov et al. [10] theoretically tested possible relationships between measures of glass stability and a criterion for glass-forming ability by computing non-isothermal crystallization kinetics for typical values of the main quantities that control nucleation and growth in silicate glasses. These quantities were the melting entropy and two kinetic parameters that control the viscosity (\( B \) and \( T_o \) in the Vogel–Fulcher–Tamman equation). The results demonstrate that glass stability and glass-forming ability are related concepts, thus reinforcing the present findings.

### Table 3

<table>
<thead>
<tr>
<th>System</th>
<th>( T_g ) (K)</th>
<th>( T_h ) (K)</th>
<th>( T_m ) (K)</th>
<th>( K_H )</th>
</tr>
</thead>
<tbody>
<tr>
<td>44NS</td>
<td>694</td>
<td>903</td>
<td>1208</td>
<td>0.68 ± 0.05</td>
</tr>
<tr>
<td>LS2</td>
<td>733</td>
<td>937</td>
<td>1303</td>
<td>0.56 ± 0.02</td>
</tr>
<tr>
<td>LS2-OH</td>
<td>733</td>
<td>932</td>
<td>1303</td>
<td>0.54 ± 0.04</td>
</tr>
<tr>
<td>BS2</td>
<td>975</td>
<td>1147</td>
<td>1686</td>
<td>0.32 ± 0.05</td>
</tr>
<tr>
<td>NC2S3</td>
<td>854</td>
<td>1016</td>
<td>1557</td>
<td>0.30 ± 0.04</td>
</tr>
<tr>
<td>N2CS3</td>
<td>755</td>
<td>883</td>
<td>1418</td>
<td>0.24 ± 0.03</td>
</tr>
<tr>
<td>Ba2TiSi2O8</td>
<td>980</td>
<td>1068</td>
<td>1703</td>
<td>0.14 ± 0.03</td>
</tr>
</tbody>
</table>

The crystallization temperatures obtained with the three types of crucibles were significantly different. As an example, the DSC traces obtained for the LS2 glass cooled at 20 K/min are shown in Fig. 5. At all the cooling rates, the crystallization temperatures observed were lower for graphite than for alumina and platinum crucibles. This result can be explained by the fact that Pt and Al2O3 influence the crystallization temperatures of LS2 (and probably of other systems), increasing and decreasing its \( q_{cr} \), respectively. As a matter of fact, Pt is a powerful nucleating agent for LS2, inducing heterogeneous nucleation at the crucible walls.
On the other hand, it is well known that alumina (which probably dissolves in the melt) increases the glass viscosity, thereby decreasing crystal nucleation and growth rates [12]. Furthermore, in certain cooling experiments, we detected different crystallization temperatures (several crystallization peaks) in repeated experiments. However, we observed only one crystallization peak in graphite crucibles. The differences among these results clearly indicate heterogeneous crystallization induced by Pt and Al₂O₃ when the molten samples were in contact with the crucible walls. This behavior was not observed with the graphite crucible because this material, whose wettability is almost non-existent, did not react with the LS₂ glass. Indeed, at the end of the experiments, the samples presented a spherical shape while, in the Pt and Al₂O₃ crucibles, the samples were distributed around the crucible walls, wetting them.

Despite the crucible effect, the overall results of this research indicate that the $K_H$ parameter, which is easy to measure, can be used to compare the relative vitrification tendency of good glass-forming systems. However, we demonstrated that the relationship between $K_H$ and $q_\alpha$ is valid only for glasses that show copious internal nucleation (in addition to surface nucleation). Therefore, due to the crucible effect and to the sensitivity of both GS and GFA to the nucleation mechanism, extreme care with the experimental procedures must be exercised when measuring these parameters. It is reasonable to assume that this technique can also be applied to reluctant glass formers, such as metallic and fluoride glasses. In this case, for instance, variations of $K_H$ with the addition of certain compounds to the base glass could be used to optimize glass-forming compositions.

6. Conclusions

The experimental critical cooling rates obtained by the CB technique, modified in this work to favor internal nucleation, were consistent with experimental observations on the melting and quenching of seven glass-forming liquids.

The critical cooling rates obtained by the CB method from experiments in Pt crucibles were one order of magnitude greater than those predicted from theoretical calculations using TTT curves. This result is due to heterogeneous nucleation on the Pt crucible walls. Despite this drawback, the critical cooling rates consistently varied with glass composition indicating that the CB method can be used to estimate the relative vitrification tendency and to compare different materials.

An empirical correlation between the Hrubý parameter of glass stability and the glass-forming tendency was demonstrated, in line with theoretical expectations.

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References