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Generalization of the Avrami equation for the analysis of non-isothermal transformation kinetics. Application to the crystallization of the $\text{Cu}_{0.20}\text{As}_{0.30}\text{Se}_{0.50}$ alloy

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Abstract

Non-isothermal differential scanning calorimetry is frequently employed to study the kinetics of the transformation reactions and, in particular, the crystallization of the glassy alloys. Such data are analyzed by the Kissinger method, which was originally derived for the study of homogeneous reactions. The consensus in the literature, in several decades, was that such applications (i.e. to heterogeneous solid state transformations) of the Kissinger method are not valid. In the present work the principal objections to these applications are addressed and alternative derivations of theoretical results are provided. These results demonstrate that the Kissinger method is valid for heterogeneous reactions of the type described by Johnson–Mehl–Avrami equation in the isothermal case. Isothermal and non-isothermal data on crystallization of the $\text{Cu}_{0.20}\text{As}_{0.30}\text{Se}_{0.50}$ glassy alloy are presented. These experimental results and the discussions presented here help to clarify the effects of incubation times in non-isothermal transformation kinetic and provide a further demonstration of validity of the generalized Johnson–Mehl–Avrami theory for the description of heterogeneous solid state transformations. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Although glass has been used as an artistic medium and industrial material for centuries it has been only in recent years that “glass science” has emerged as a field of study in its own right. The last decades have seen a strong theoretical and practical interest in the application of isothermal and non-isothermal experimental analysis techniques to the study of glass–crystal transformations. While isothermal experimental analysis techniques are in most cases more definitive, non-isothermal thermoanalytical techniques have several advantages. The rapidity with which non-isothermal experiments can be performed makes these types of experiments attractive. Non-isothermal experiments can be used to extend the temperature range of

measurements beyond that accessible to isothermal experiments. Many phase transformations occur too rapidly to be measured under isothermal conditions because of transients inherently associated with the experimental apparatus. Industrial processes often depend on the kinetic behavior of systems undergoing phase transformation under non-isothermal conditions. In this instance a definitive measurement of non-isothermal transformation kinetics is desirable.

The study of crystallization kinetics in glass-forming liquids has often been limited by the elaborate nature of the experimental procedures that are employed. The increasing use of thermoanalytical techniques such as differential thermal analysis (DTA) or differential scanning calorimetry (DSC) has, however, offered the promise of obtaining useful data with simple methods. A popular thermal analysis method developed by Kissinger [1,2] determines the kinetic parameters from graphs of the logarithm of the temperature squared, T_p , at the maximum of the reaction rate versus the reciprocal of T_p in non-isothermal experiments. This method

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was frequently used in studies of the crystallization of glassy alloys [3–8] despite the fact that literature [9] on thermal analysis techniques reflected a consensus that application of the Kissinger method to solid state reactions is improper. However, the notable work of Henderson [10] has provided a theoretical basis for the treatment of non-isothermal analysis techniques and justifies the use of the Kissinger method for many solid state transformations. The three main objections to the use of this method for study of solid state reactions were: (1) thermal gradients are inherent in non-isothermal methods. Thus, it was claimed that significant inaccuracy will result from the application of the Kissinger method which does not allow for the presence of temperature gradients. (2) The reaction rate equation which is appropriate for isothermal experiments is assumed in the Kissinger analysis. It is frequently argued that a term involving the temperature partial derivative must be included in the analysis of non-isothermal experiments; this point has been debated in the literature for over several years. (3) The order of reaction equation assumed in the Kissinger analysis is appropriate for homogeneous transformations, (e.g. chemical reactions in a gas) but is not valid for the heterogeneous transformations which generally occur in solid state reactions.

Regarding the first objection, it is possible to describe simple procedures to reduce the influence of temperature gradients to negligible levels.

The confusion in the literature surrounding the proper form of the reaction rate equation in the Kissinger analysis (objection (2)) results from the assumption that the progress of a reaction can be described as a simple function of time and temperature. The volume fraction transformed is clearly a functional [11], dependent on the temperature history, and not a simple function. However, a result of the analysis presented in this paper and the principal assumption in Henderson's work [10] is that the reaction rate is an ordinary function of the temperature and the volume fraction transformed.

As for the third objection, Henderson [10] has shown that the Kissinger method can be applied to the analysis of many heterogeneous reactions. In the present work, an alternative treatment of non-isothermal transformation kinetics is provided. The quoted treatment indicates that the Kissinger method can be applied to any reaction of the type described by the Johnson–Mehl–Avrami (JMA) equation [12–15] in the isothermal case. The treatment presented here (as does that of Henderson) goes as follows: (i) generalize the JMA approach to deal with non-isothermal heterogeneous reactions, and (ii) demonstrate that in the constant heating rate case (within negligible errors) the Kissinger relationship obtains.

Finally, isothermal and non-isothermal data on the crystallization of $\text{Cu}_{0.20}\text{As}_{0.30}\text{Se}_{0.50}$ glassy alloy are presented. Results on the influence of incubation times on non-isothermal experiments are included. The data are in good agreement with the theoretical results.

2. Theoretical basis

In the DSC the instrument supplies heat to either the sample being investigated or the reference material in order to keep their temperatures equal. The instantaneous heat supplied to the sample or reference is available as the output signal. The fraction of material transformed at any time is proportional to the amount of heat evolved. During crystallization of the glass an exothermic peak is observed because the enthalpy of the crystal is lower than that of the glass. The enthalpy corresponding to the area under the peak is equal to the heat of reaction.

2.1. Isothermal treatment

The JMA equation [12–15] describes a wide variety of isothermal solid state transformations and has the form

$$x(t) = 1 - \exp[-(Kt)^n] \quad (1)$$

where x is the volume fraction transformed after time t , n is a quantity called kinetic exponent, which depends on the mechanism of growth and the dimensionality of the crystal, and K is the reaction rate constant, whose temperature dependence is generally expressed by the Arrhenius equation:

$$K(T) = K_0 \exp(-E/RT) \quad (2)$$

where K_0 is the frequency factor, T is the absolute temperature, and E is activation energy for the transformation process with R the gas constant. Note that Eq. (1) describes isothermal processes so $K(T)$ is a constant (which depends on the temperature). An expression for the reaction rate, dx/dt , can be derived by differentiating Eq. (1) with respect to t , at constant temperature, giving

$$dx/dt = nK^n t^{n-1} (1-x) = nK(1-x)[- \ln(1-x)]^{(n-1)/n} \quad (3)$$

which is a simple function of the temperature and the volume fraction transformed.

When an isothermal experiment is performed using a DSC, the rates of crystallization at various times, dx/dt , are measured directly. However, the results can be more easily analyzed by Eq. (1). Taking twice the logarithm of Eq. (1) leads to the expression

$$\ln[- \ln(1-x)] = n \ln K + n \ln t. \quad (4)$$

At a given temperature, values of n and K are determined from an isothermal DSC curve using Eq. (4) by least-squares fitting of $\ln[- \ln(1-x)]$ versus $\ln t$. Values of $\ln K$ are evaluated at different temperatures by repeating the same procedure. The activation energy and frequency factor are then evaluated from the logarithmic form of Eq. (2) by least-squares fitting $\ln K$ versus $1/T$.

2.2. Non-isothermal treatment

It is very interesting to generalize Eq. (1) to treat experiments in which temperature is a function of time. If it is

assumed that the transformation products and mechanism do not change with temperature, then it is reasonable to interpret Kt in Eq. (1) as being proportional to the number of atomic jumps within the interval t at temperature T . It is assumed that the progress of the transformation is determined by the number of atomic jumps in the general (non-isothermal) case, then Eq. (1) generalizes to

$$x(t) = 1 - \exp \left[- \left(\int_0^t K[T(t')] dt' \right)^n \right] = 1 - \exp(-I^n) \quad (5)$$

where $K[T(t')]$ is still given by Eq. (2) and $T(t')$ is the temperature at t' . Note that the volume fraction crystallized depends on t and the temperature history $T(t')$ for times t' earlier than t and the same is true for the integral I .

Differentiating Eq. (5) with respect to time, the crystallization rate is obtained as

$$dx/dt = nK(1-x)I^{n-1}. \quad (6)$$

The maximum crystallization rate is found by making $d^2x/dt^2 = 0$, thus obtaining the relationship

$$nK_p(I^n)_p = \beta EI_p/RT_p^2 + (n-1)K_p \quad (7)$$

in which $\beta = dT/dt$ is the heating rate for a non-isothermal process, and where the magnitude values which correspond to the maximum crystallization rate are denoted by subscript p .

By using the substitution $y' = E/RT'$ the integral I can be represented by the alternating series [16]

$$-e^{-y'} y'^{-2} \sum_{k=0}^{\infty} \frac{(-1)^k (k+1)!}{y'^k}$$

where it is possible to use only the two first terms, without making any appreciable error, and to obtain

$$I = RT^2 K(\beta E)^{-1} (1 - 2RT/E), \quad (8)$$

if it is assumed that $T_0 \ll T$ (T_0 is the starting temperature), so that y_0 can be taken as infinity.

Substituting the last expression of I in Eq. (7), one obtains

$$I_p = (1 - 2RT_p/nE)^{1/n}$$

relationship that when it is equated to Eq. (8) gives

$$RT_p^2 (\beta E)^{-1} K_0 \exp(-E/RT_p) = (1 - 2RT_p/nE)^{1/n} \times (1 - 2RT_p/E)^{-1} \quad (9)$$

or in a logarithmic form

$$\ln(T_p^2/\beta) + \ln K_0 R/E - E/RT_p \approx (2RT_p/E)(1 - 1/n^2) \quad (10)$$

where the function $\ln(1-z)$ with $z = 2RT_p/nE$ or $z = 2RT_p/E$ is expanded as a series and where only the first term of itself has been taken.

Note that Eq. (10) reduces to the Kissinger expression for the $n = 1$ case as one might have anticipated since this corresponds to the homogeneous reaction case. Moreover, for most crystallization reactions the right-hand side (RHS)

of Eq. (10) is generally negligible in comparison to the individual terms on the left hand side for common heating rates ($\leq 100 \text{ K min}^{-1}$). Thus, it can be seen that the Kissinger method is appropriate for the analysis not only of homogeneous reactions, but also for the analysis of heterogeneous reactions which are described by the JMA equation in isothermal experiments. The approximation in Eq. (10), RHS = 0 implies

$$d[\ln(T_p^2/\beta)]/d(1/T_p) = E/R,$$

where the quoted approximation might introduce a 3% error in the value of E/R in the worst cases. (Typically, $n > 1$ and $E/RT_p > 25$ which suggests that the error introduced in E/R by setting the RHS of Eq. (10) equal to 0 is considerably less than 1%). Eq. (10) also serves to determine the frequency factor, K_0 , from the intercept of a $\ln(T_p^2/\beta)$ versus $1/T_p$ plot. Eq. (6), which describes the time dependence of the reaction rate, and Eq. (10), which allows for the simple extraction of the parameters K_0 and E by means of the Kissinger method, form the basis for the analysis of constant heating rate data.

Finally, it should be noted that the Eq. (10) with RHS = 0 is obtained, considering that the term $2RT/E$ in Eq. (8) is negligible in comparison to unity, since in most crystallization reactions $E/RT \gg 1$ (usually $E/RT \geq 25$) [17]. Bearing in mind this assumption, Eq. (8) for the maximum crystallization rate may be rewritten as

$$I_p = RT_p^2 K_p (\beta E)^{-1}$$

an expression which when substituted into Eq. (7) gives $I_p = 1$, and then Eq. (6) permits to obtain

$$n = (dx/dt)_p RT_p^2 (0.37\beta E)^{-1} \quad (11)$$

which makes it possible to calculate the kinetic exponent n .

3. Experimental procedures

High purity (99.999%) copper, arsenic and selenium in appropriate atomic percent proportions were weighed into a quartz glass ampoule (6 mm diameter). The contents of the ampoule (7 g total) were sealed at a pressure of 10^{-4} Torr (10^{-2} N m^{-2}) and heated in a rotating furnace at around 950°C for 3 h, submitted to a longitudinal rotation of 1/3 rpm in order to ensure the homogeneity of the molten material, and then quenched in air to avoid crystallization of the compound. The amorphous nature of the material was checked through a diffractometric X-ray scan, in a Siemens D500 diffractometer. The thermal behavior was investigated using a Perkin-Elmer DSC7 differential scanning calorimeter with an accuracy of $\pm 0.1^\circ\text{C}$. Temperature and energy calibrations of the instrument were performed using the well-known melting temperatures and melting enthalpies of high-purity zinc and indium supplied with the instrument. Powdered samples weighing about 20 mg (particle size around $40 \mu\text{m}$) were crimped in aluminum pans, an empty aluminum pan was used as reference, and

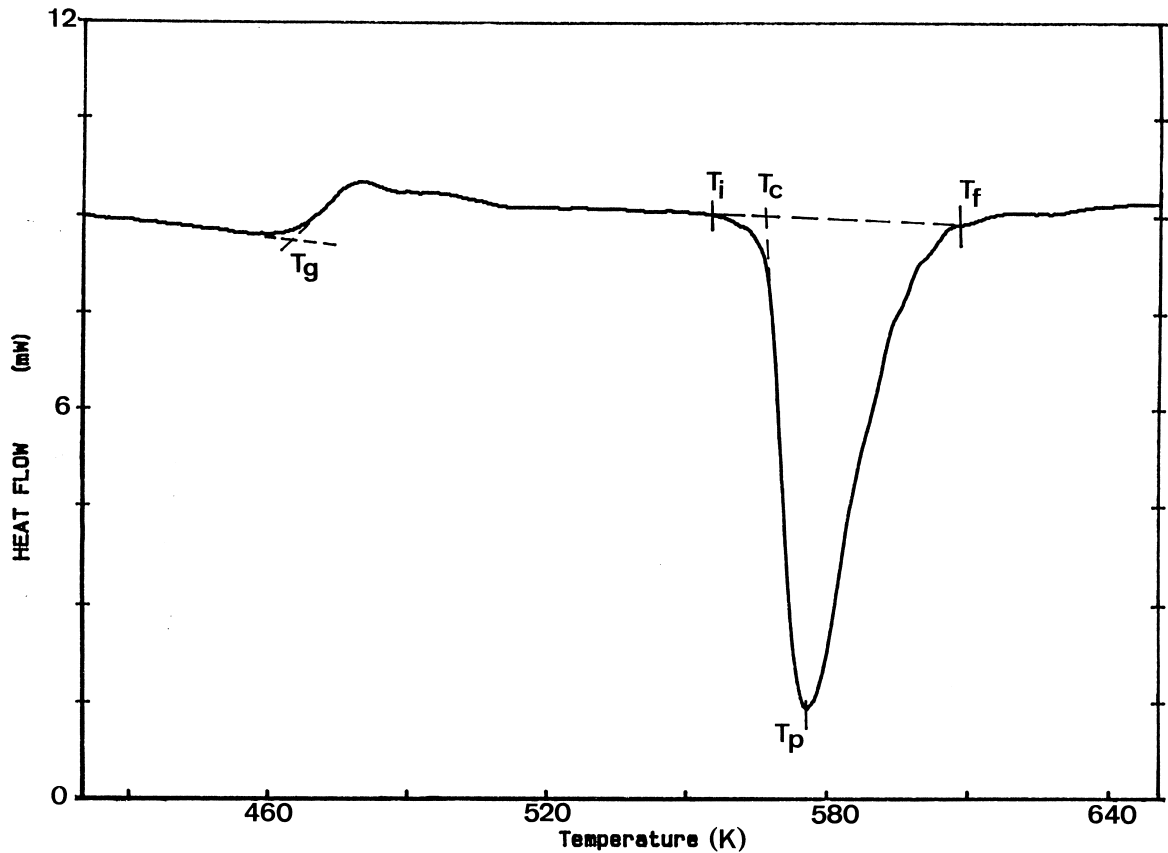


Fig. 1. Typical DSC trace of $\text{Cu}_{0.20}\text{As}_{0.30}\text{Se}_{0.50}$ glassy alloy at a heating rate 16 K min^{-1} .

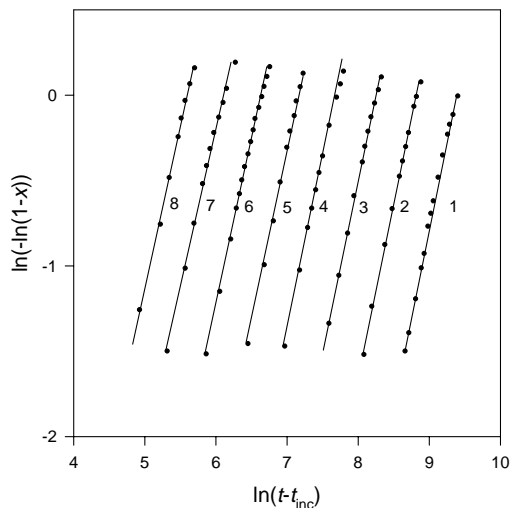


Fig. 2. Plots for extracting the kinetic exponent, n , in Eq. (1), as described in the text. Characteristic parameters are listed in Table 1 for the corresponding curve number.

a constant flow of nitrogen was maintained in order to drag the gases emitted by the reaction, which are highly corrosive to the sensory equipment installed in the DSC furnace.

Isothermal transformation kinetics data for the $\text{Cu}_{0.20}\text{As}_{0.30}\text{Se}_{0.50}$ glassy alloy were obtained by monitoring the time dependence of the DSC output for a series of temperatures. The DSC output, Q_{DSC} , is assumed to be proportional to the reaction rate, dx/dt , ($Q_{\text{DSC}} = C dx/dt$, C is a constant) so the volume fraction crystallized, $x(t)$, is given by $x(t) = A(t)/A$ where

$$A(t) = \int_0^t Q_{\text{DSC}} dt' = C[x(t) - x(0)]$$

and $A = A(\infty)$. The technique for extracting the time exponent n and $K(T)$ in an isothermal experiment described by Eq. (1) is to plot $\ln\{\ln[A/(A - A(t))]\}$ versus $\ln t$, so that n is the slope and $K(T) = t_0^{-1}$ where t_0 is the time in seconds when $\ln\{\ln[A/(A - A(t))]\} = 0$.

Non-isothermal transformation kinetics data for the above-mentioned alloy were obtained by scanning of the samples at room temperature through their glass transition temperature, T_g , at different heating rates: 2, 4, 8, 16, 32 and 64 K min^{-1} . The typical DSC trace of $\text{Cu}_{0.20}\text{As}_{0.30}\text{Se}_{0.50}$ chalcogenide glass obtained at a heating rate of 16 K min^{-1} and

Table 1
 Experimental and theoretical parameters for isothermal and constant heating rate experiments on $\text{Cu}_{0.20}\text{As}_{0.30}\text{Se}_{0.50}$ glassy alloy

Isothermal				Constant heating rate							
Run	T (K)	t_{inc} (s)	n	Run	β (K min^{-1})	T_p , Exp. (a) (K)	T_p , Exp. (p) (K)	T_p , theory (K)	FWHM, Exp. (a) (K)	FWHM, Exp. (p) (K)	FWHM, theory (K)
1	513	2573	2.06	1	2	554.2	548.2	547.0	7.2	10.8	11.9
2	518	1240	2.03	2	4	561.0	554.9	553.7	8.1	11.5	12.2
3	523	459	2.01	3	8	568.0	561.6	560.5	8.1	11.5	12.5
4	528	201	1.95	4	16	575.3	568.4	567.5	8.2	12.5	12.8
5	533	111	1.98	5	32	582.6	575.4	574.6	9.0	12.5	13.2
6	538	55	1.93	6	64	590.2	582.6	582.0	11.1	13.3	13.4
7	543	39	1.84								
8	548	20	1.90								

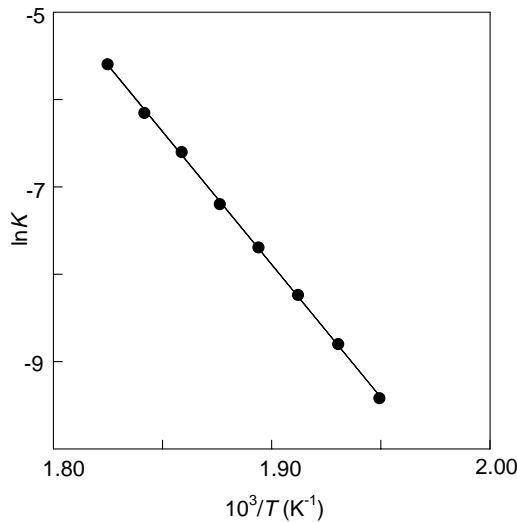


Fig. 3. The logarithm of the reaction rate constant, K , deduced from the isothermal measurements is plotted against $1/T$ (K is in s^{-1}).

plotted in Fig. 1 shows three characteristic phenomena which are resolved in the temperature region studied. The first ($T = 465.8$ K) corresponds to the glass transition temperature T_g , the second ($T = 568.0$ K) to the extrapolated onset crystallization temperature T_c , and the third ($T = 575.3$ K) to the peak temperature of crystallization T_p of the above-mentioned chalcogenide glass. This behavior is typical for a glass–crystal transformation. It should be noted that the temperature values: T_g , T_c and T_p increase with increasing heating rate, as often noted in the literature [18].

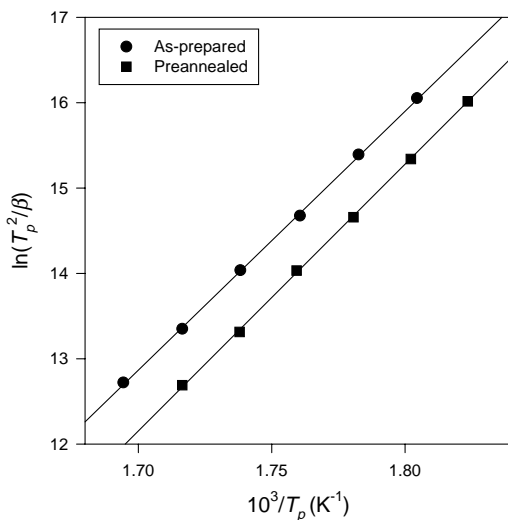


Fig. 4. Plots of $\ln(T_p^2/\beta)$ versus $1/T_p$ and straight regression lines for as-prepared and pre-annealed samples.

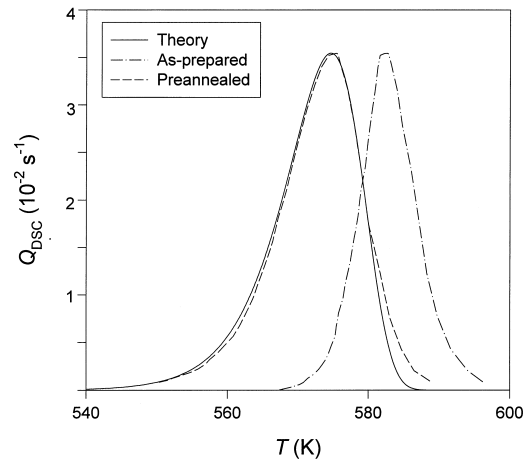


Fig. 5. Experimental and theoretical DSC traces for 32 K min^{-1} heating rate. Parameters used in the theoretical curve were obtained from isothermal data ($E = 60.9$ kcal mol^{-1} ; $K_0 = 5.11 \times 10^{21}$ s^{-1} and $\langle n \rangle = 1.96$). Area of the theoretical curve is normalized to unity. Peak heights of the experimental curves were scaled to match the theoretical curve. Experimental data are shown for the as-prepared and pre-annealed samples.

4. Results and discussion

The isothermal DSC measurements exhibit an “incubation time”, t_{inc} , during which no observable transformation occurs. The temperature dependence of t_{inc} can be described as an activated process with an energy close to that for the phase transformation; this is often observed in studies of crystallization [19].

The DSC traces for a series of temperatures were integrated to yield plots of $\ln[-\ln(1 - A(t)/A)]$ versus $\ln(t - t_{\text{inc}})$ which are shown in Fig. 2. Reasonably good straight lines are obtained; the n values determined from Fig. 2, and given in Table 1 for different temperatures, range from 1.84 to 2.06 with a mean value of 1.96. The deviation from linearity at long times may reflect breakdown of the theory for $x(t)$ at the end of the transformation.

The logarithm of the rate constant K , obtained from Fig. 2 is plotted against $1/T$ in Fig. 3. The slope of the line, obtained from a least-squares fit, gives $E = 60.9$ kcal mol^{-1} for the activation energy and the intercept of the above-mentioned line gives $K_0 = 5.11 \times 10^{21}$ s^{-1} for the frequency factor. There is little scatter about the lines in Figs. 2 and 3 despite the inherent experimental difficulties in establishing accurate baselines with this method.

The non-isothermal data for the $\text{Cu}_{0.20}\text{As}_{0.30}\text{Se}_{0.50}$ glassy alloy, obtained at the heating rates given in Table 1, were analyzed by using Eq. (10) with RHS = 0 and Eq. (11) deduced in the preceding theory. The plot of $\ln(T_p^2/\beta)$ versus $1/T_p$ is shown in Fig. 4. A good straight line with little scatter results, yielding $E = 60.6$ kcal mol^{-1} for the activation energy and $K_0 = 1.90 \times 10^{21}$ s^{-1} for the frequency

factor. The mean value of the kinetic exponent, according to Eq. (11), is $\langle n \rangle = 1.99$.

Also shown in Fig. 4 are constant heating rate data obtained on a set of $\text{Cu}_{0.20}\text{As}_{0.30}\text{Se}_{0.50}$ samples which had been previously annealed through the incubation time (1200 s at 518 K) as determined in the isothermal experiments. It is possible to assume that this pre-anneal eliminates the effect of incubation in the constant heating rate experiments so as to permit direct comparisons with theory. (Recall that incubation is not described by the JMA theory, although the subsequent reaction is in the isothermal case.) The resulting values for E and K_0 are $62.5 \text{ kcal mol}^{-1}$ and $1.94 \times 10^{22} \text{ s}^{-1}$, respectively. These compare well with the above-mentioned isothermal values.

As a further check on the adequacy of the generalized JMA equation for describing constant heating rate experiments, the DSC peak positions and shapes were computed from Eq. (6) using the values of E , K_0 and n determined from the isothermal measurements. Fig. 5 shows typical computed and experimental results obtained in constant heating rate experiments including the effect of pre-annealing through the incubation time. Generally, for pre-annealed samples the DSC peak positions are within 2 K of the predicted positions, the full width at half maximum (FWHM) is within 1 K, and the predicted asymmetry is observed. Unannealed samples exhibit narrower and less skewed DSC peaks than given by the generalized JMA theory. Table 1 summarizes the predicted and observed values of T_p and FWHM, both for as-prepared and pre-annealed samples, at the heating rates employed in this study. It should be noted that the theoretical constant heating rate curves were based upon the best fit isothermal parameters and are skewed such that the right half maximum point lies approximately 2/3 as far from the maximum as the left half maximum point. This asymmetry is not seen with as-prepared samples (Exp. (a)) but is present in the pre-annealed samples (Exp. (p)).

5. Summary and conclusions

The JMA theory provides a satisfactory description of the isothermal transformations as illustrated in Fig. 2. Thus, the JMA equation, Eq. (1), (rather than the order of reaction equation) was adopted as a basis for the study of non-isothermal transformations. A generalization appropriate for an arbitrary temperature–time history was required. As described earlier, the fraction transformed, $x(t)$, must be a functional of the function $T(t')$ for all $t' < t$. An analogous case is found in Cahn's additivity criterion [20] for analyzing the progress of a reaction along an arbitrary path in a T – T diagram. A surprising result of this analysis, and that provided by Henderson [10], is that in the constant heating rate case, the descriptive equation, Eq. (10), is essentially independent of the kinetic exponent, n , and that the Kissinger equation holds. Thus, although the basic equation

in Kissinger's analysis of homogeneous transformations is indeed inappropriate for heterogeneous solid state transformations, the Kissinger method can be applied to the analysis of heterogeneous transformations. Also, it is possible understand why the Kissinger method had previously been successfully applied to the fitting of constant heating rate data in many studies of heterogeneous solid state reactions.

The validity of the theoretical description of the non-isothermal transformation case is indicated by the agreement observed in the kinetic parameters extracted from the isothermal and from the constant heating rate measurements in $\text{Cu}_{0.20}\text{As}_{0.30}\text{Se}_{0.50}$ glassy alloy. This agreement is particularly good for the samples in which the effects of incubation were removed by pre-annealing; the values for E and $\ln K_0$ agree within 2.7% which is within the limit of error inherent in the measurements. Another way of assessing the non-isothermal theory is to use the kinetic parameters deduced from isothermal studies to predict non-isothermal DSC curves. The close agreement between the observed and predicted DSC peak temperature, T_p , full width at half maximum, FWHM, and asymmetry then stand as support for the correctness of the theoretical approach. It is possible to attribute the somewhat poorer results on the unannealed samples to the fact that the JMA equation does not describe incubation effects. An incubation time can be expected to inhibit the transformation on the low-temperature side of the reaction rate peak in a non-isothermal experiment resulting in a less skewed peak, as observed.

The principal results may be summarized as follows: (i) Henderson's assumption [10] that the JMA reaction rate equation holds for arbitrary temperature history and the assumption that the volume fraction crystallized is determined by the number of atom movements for arbitrary temperature history as described herein lead to equivalent theories and, in the non-isothermal case, indicate that the Kissinger method can be used to extract kinetic parameters. (ii) The results obtained in samples of the $\text{Cu}_{0.20}\text{As}_{0.30}\text{Se}_{0.50}$ glassy alloy exhibiting incubation effects in the isothermal case are seen to be approximately described by the quoted theory. Moreover, it is shown that when incubation effects are eliminated, by pre-annealing, detailed agreement with theory is obtained. Thus, in the present work in the pre-annealed samples, the DSC peak positions, FWHM and asymmetry obtained in non-isothermal measurements are in remarkable agreement with the theoretical predictions based upon kinetic parameters deduced from isothermal experiments. Also the kinetic parameters deduced from non-isothermal experiments and those from isothermal experiments agree within experimental uncertainties.

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