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THERMAL DECOMPOSITION OF PURE PIROXICAM AND ITS SURFACE DEPOSIT ON AMORPHOUS SILICON DIOXIDE: MECHANISM AND KINETIC DATA

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ABSTRACT

The thermal behaviour of piroxicam (white anhydrous form) and its surface deposit (50 wt.%) on amorphous silicon dioxide was studied using TG and DSC techniques. On the basis of isothermal TG, thermal decomposition kinetic data were obtained and reaction mechanisms were established according to Sharp's method. It was found that the thermal decomposition of pure piroxicam was heterogeneous, but that the surface deposit decomposed homogeneously throughout the whole reaction.

INTRODUCTION

The majority of papers on thermogravimetry are published in the fields of analytical and inorganic chemistry in spite of the fact that the study of organic and polymer compounds is of equal importance.

In analytical chemistry, thermogravimetry is invaluable for investigating the suitable weighing forms of many compounds, in testing materials that are actual or potential primary standards and as a direct technique for analytical determinations.

In the literature [1], the combined use of isothermal and non-isothermal thermogravimetry for kinetic determinations, with the objective of the elimination of some of their particular limitations, has been described. Non-isothermal methods offer particular advantages for the kinetic determination of chemical reactions in the solid phase [2], while isothermal methods are much more efficient for the identification of the reaction mechanism.

To obtain kinetic data with isothermal thermogravimetry, the material is heated isothermally under stated conditions. The data are collected in the form of α against t plots (Fig. 1), where α is the fraction decomposed and t

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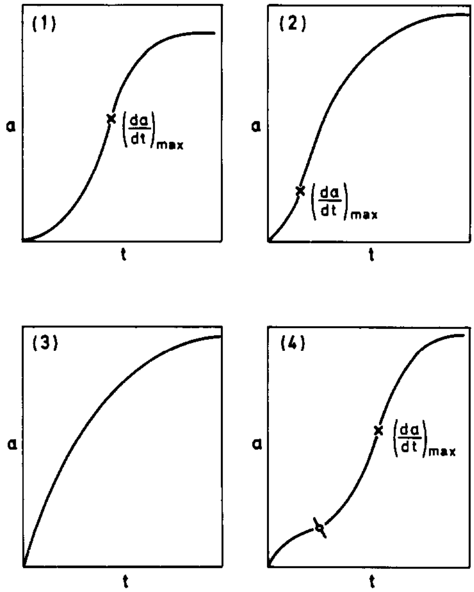

Fig. 1. Typical α against t plots for the thermal decomposition of the solids: 1, sigmoid—autocatalytic; 2, short induction or initial period, mostly decreasing rate; 3, no induction period; 4, very long induction period with some evolution of gas.

is the time of heating. Repeating these experiments at different temperatures allows the calculation of the activation energy.

In most homogeneous reactions, the entire decomposition fits one kinetic law. In heterogeneous decompositions, one expression may hold for the initial stage of the decomposition, to be followed by a second in the accelerating stage of the reaction. A third or even fourth expression may be necessary to describe the reaction in the decelerating decomposition stage.

Thermal decomposition may start with the induction period when the decomposition rate increases with time. This is due to nucleation of a new phase. Decomposition often begins without an induction period, so that nucleation and new phase nucleus growth are not separate [3].

To recognize the reaction mechanism, two methods are available: in the first the so-called reduced time plots are used, while in the second the generalized use of Avrami–Erofeev plots is employed. The method of reduced time plots was derived by Sharp et al. [4], although some of the functions had been treated in a similar manner by Giess [5]. In Sharp's method, solid state reactions are represented by equations of the type $F(\alpha) = kt$, where α is the fraction of material reacted in time t. These equations can be expressed in the $F(\alpha) = A(t/t_{0.5})$ form where $t_{0.5}$ represents the time taken for 50% reaction and A is a calculable constant depending on the form of $F(\alpha)$. In the literature [4], numerical tables are given for $F(\alpha)$ in relation to α, and to $(t/t_{0.5})$, for nine equations corresponding to reactions which are diffusion- or reaction-rate-controlled, or

TABLE 1

Equations for the description of the thermal decomposition of the solid components

Equation	Rate-controlling process
$\alpha^2 = kt$	(D_1) One-dimensional diffusion
$(1-\alpha)\ln(1-\alpha)+\alpha = kt$	(D_2) Two-dimensional diffusion; cylindrical symmetry
$(1-(1-\alpha)^{1/3})^2 = kt$	(D_3) Three-dimensional diffusion; spherical symmetry; Jander equation
$(1-2/3\ \alpha)-(1-\alpha)^{2/3} = kt$	(D_4) Three-dimensional diffusion; spherical symmetry; Ginstling and Brounstein equation
$-\ln(1-\alpha) = kt$	(F_1) Random nucleation; only one nucleus on each particle
$(-\ln(1-\alpha))^{1/2} = kt$	(A_2) Random nucleation; Avrami–Erofeev I equation
$(-\ln(1-\alpha))^{1/3} = kt$	(A_3) Random nucleation; Avrami–Erofeev II equation
$1-(1-\alpha)^{1/2} = kt$	(R_2) Phase boundary reaction; cylindrical symmetry
$1-(1-\alpha)^{1/3} = kt$	(R_3) Phase boundary reaction; spherical symmetry

obey first-order kinetics, or follow the equations of Avrami and Erofeev (Table 1).

EXPERIMENTAL

Kinetic data and the reaction mechanism were studied for the thermal decomposition of pure micronized piroxicam (Krka, Yugoslavia) and the surface deposit (50 wt.%) of piroxicam on amorphous silicon dioxide—Aerosil^R 380 (Degussa, FRG).

Thermogravimetrical analyses were performed on a Mettler thermoanalyser TA 1 with Al_2O_3 as a reference, in a dynamic air atmosphere. Other operating conditions were: mass of sample, 10 mg; sample holder, platinum crucible; and air flow speed, 5 l h^{-1}.

DSC curves were performed on a Mettler thermoanalyser TA 2000C with scan speed 10 K min^{-1} in an air atmosphere with 25 ml min^{-1} flow speed and with Al_2O_3 as a reference.

RESULTS AND DISCUSSION

Piroxicam is a well-known non-steroid anti-inflammatory drug with a relatively low dissolution rate. Some surface deposits on various porous and non-porous types of SiO_2 were prepared to enhance this rate [6].

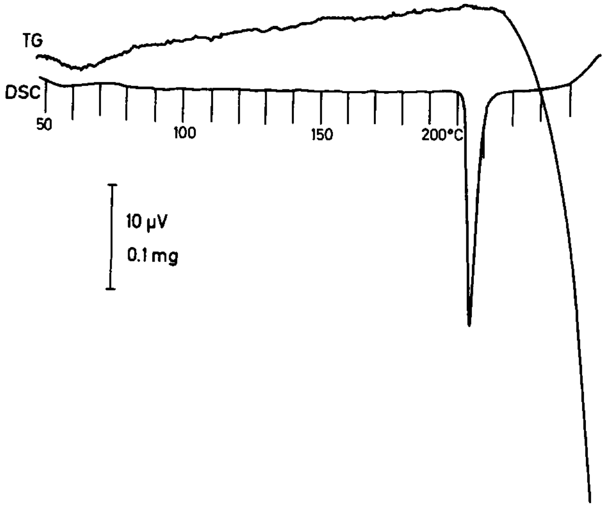

Fig. 2. DSC and TG curves for micronized piroxicam (white anhydrous form).

Early DSC and TG studies of piroxicam and its surface deposits suggested that the thermal stability of the surface deposit was variable (Figs. 2 and 3). Consequently, isothermal thermogravimetry was used to explain and confirm the expected differences.

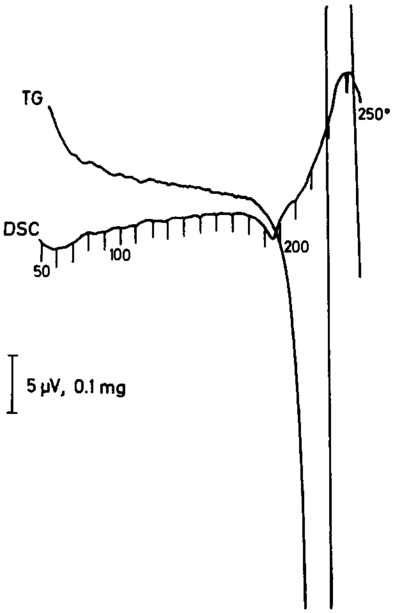

Fig. 3. DSC and TG curves for decomposition of surface deposit of micronized piroxicam (white anhydrous form) on Aerosil^{R} 380.

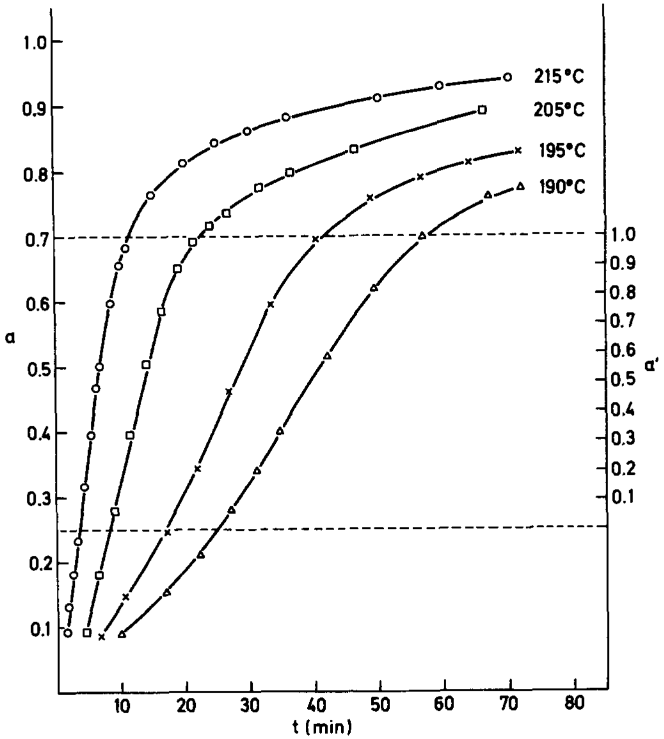

Fig. 4. α vs. t plots for isothermal decomposition of micronized piroxicam.

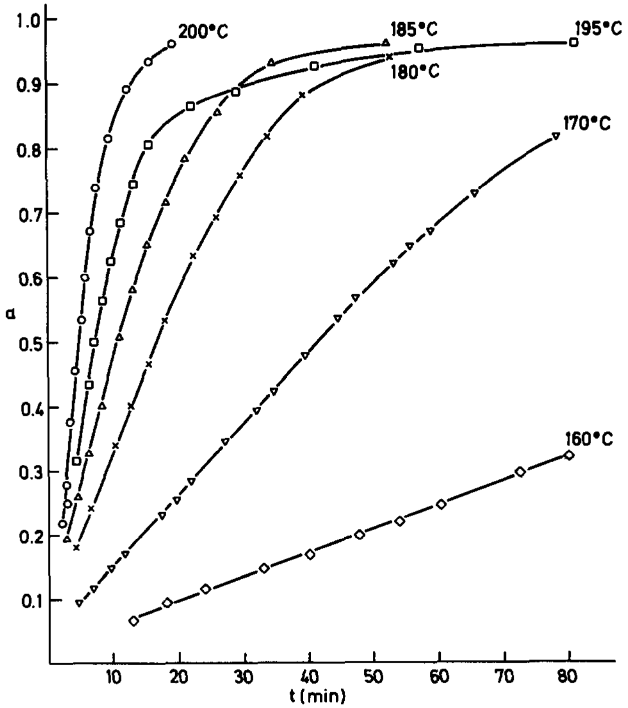

Fig. 5. α vs. t plots for isothermal decomposition of surface deposit of micronized piroxicam on Aerosil^{R} 380.

TABLE 2

Theoretical and experimental $t/t_{0.5}$ values for piroxicam (R_2 mechanism according to Sharp's method [4]. $t=0$, $\alpha'=0$ at $\alpha=0.25$; $\alpha'=1$ at $\alpha=0.70$

α'	Theor. $t/t_{0.5}$	Exp. $t/t_{0.5}$					
		190 °C	195 °C	200 °C	205 °C	210 °C	215 °C
0.1	0.174	0.221	0.212	0.214	0.231	0.162	0.207
0.2	0.362	0.421	0.424	0.400	0.442	0.378	0.483
0.3	0.556	0.607	0.626	0.571	0.654	0.541	0.655
0.4	0.768	0.793	0.818	0.800	0.788	0.757	0.828
0.5	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.6	1.253	1.200	1.253	1.157	1.231	1.189	1.276
0.7	1.543	1.421	1.455	1.357	1.500	1.405	1.517
0.8	1.887	1.635	1.687	1.643	1.789	1.676	1.897
0.9	2.334	1.924	2.010	1.957	2.173	2.216	2.241
k (reaction constant)		0.0326	0.0455	0.0661	0.0791	0.1075	0.1355
r [a]		0.9624	0.9601	0.9546	0.9408	0.9351	0.9392

[a] Correlation coefficient r is calculated from an R_2/t plot.

In α against t plots for the decomposition of pure micronized piroxicam and its surface deposit on Aerosil^R 380, a difference is noticed: decomposition of the surface deposit starts without an induction period, while pure piroxicam decomposes with a short induction period, particularly at lower experimental temperatures (Figs. 4 and 5).

Experimental data (α,t) for the whole decomposition reaction for $\alpha=0.1$–0.9 were tested using Sharp's method [4]. The $t/t_{0.5}$ values were compared with theoretical ones and the mechanism of decomposition was established.

α against t plots for thermal decomposition of pure piroxicam consist of several sections, i.e. decomposition is a combination of a number of mechanisms. Different mechanisms coincide at $\alpha=0.2$–0.3 and at $\alpha=0.65$–0.75. The first section of the decomposition was not analysed in detail. The start of the second part of the decomposition was defined by extrapolation ($t=0$, $\alpha'=0$). Experimental $t/t_{0.5}$ values in the section $\alpha=0.25$–0.70 fitted best to the theoretical values for an R_2 mechanism: $1-(1-\alpha)^{1/2}=kt$ (phase boundary controlled reaction for circular disc or cylinder) (Table 2). Thermal decomposition of pure piroxicam in the third section (above $\alpha=0.70$) was very slow and its mechanism was not defined.

Experimental $t/t_{0.5}$ values for the whole thermal decomposition reaction of the surface deposit are in accordance with theoretical values for an R_3 mechanism: $1-(1-\alpha)^{1/3}=kt$ (phase boundary controlled reaction, spherical symmetry) (Table 3).

The acceleratory part of the isothermal plots (their upper limit is $(d\alpha/dt)_{max}$ at $\alpha=0.5$) can be expressed using the exponential law $\alpha=kt^n$, with

TABLE 3

Theoretical and experimental $t/t_{0.5}$ values for surface deposit (R_3 mechanism according to Sharp's method [4])

α	Theor. $t/t_{0.5}$	Exp. $t/t_{0.5}$					
		160 °C	170 °C	180 °C	190 °C	195 °C	200 °C
0.1	0.165	0.161	0.135	0.133	0.152	0.186	0.213
0.2	0.349	0.364	0.363	0.289	0.288	0.357	0.404
0.3	0.544	0.567	0.578	0.524	0.495	0.614	0.575
0.4	0.762	0.785	0.792	0.759	0.762	0.800	0.787
0.5	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.6	1.277	1.237	1.232	1.247	1.286	1.286	1.192
0.7	1.607	1.611	1.500	1.578	1.619	1.643	1.404
0.8	2.014	2.135	2.074	1.946	2.095	2.157	1.915
k (reaction constant)		0.0015	0.0048	0.0125	0.0185	0.0281	0.0496
r [a]		0.9981	0.9966	0.9993	0.9995	0.9983	0.9966

[a] Correlation coefficient r is calculated from an R_3/t plot.

the Avrami–Erofeev equation $1-\alpha = \exp(-kt^n)$, or the linear law $\alpha = kt$ [3]. The most frequent values in the literature for the exponential law are 2, 3, 4 and 6. There are some examples when n is between 1 and 2 [7], as in our example. Table 4 lists n values for the exponential law and the Avrami–Erofeev equation. Their values are all about 1 for both expressions, and the reaction constants k are calculated from the linear law $\alpha = kt$ (Table 5).

Having obtained the evidence that the reaction was isokinetic at different temperatures, the Arrhenius equation $k = Ae^{-E/RT}$ was used to establish E, the activation energy. This involves plotting ln k against $1/T$ and the slope

TABLE 4

Values for n for the exponential law and the Avrami–Erofeev equation for isothermal decomposition of piroxicam and surface deposit

T(°C)	Piroxicam		Surface deposit	
	Expon. law	Avr.–Erof. eqn.	Expon. law	Avr.–Erof. eqn.
160			0.881 (0.999)	1.024 (0.998)
170			0.800 (0.998)	0.928 (0.994)
180			0.785 (0.999)	0.914 (0.999)
185			0.833 (0.994)	0.973 (0.997)
190	1.292 (0.999)	1.415 (0.994)		
195	1.259 (0.999)	1.462 (0.997)	0.936 (0.998)	1.089 (0.998)
200	1.211 (0.998)	1.405 (0.995)	1.047 (0.999)	1.219 (0.999)
205	1.221 (0.998)	1.419 (0.997)		
210	0.932 (0.994)	1.079 (0.989)		
215	1.047 (0.999)	1.219 (0.999)		

Correlation coefficients in parentheses.

TABLE 5

k values for the linear law for isothermal decomposition of piroxicam and surface deposit

T (°C)	k values	
	Piroxicam	Surface deposit
160		0.0035 (0.999)
170		0.0109 (0.999)
180		0.252 (0.999)
185		0.0374 (0.999)
190	0.0152 (0.999)	
195	0.0214 (0.999)	0.0642 (0.972)
200	0.0307 (0.999)	0.0994 (0.995)
205	0.0400 (0.999)	
210	0.0541 (0.998)	
215	0.0734 (0.998)	

Correlation coefficients in parentheses.

TABLE 6

Activation energies E for isothermal decomposition of piroxicam and surface deposit

	E (kJ mol^{-1})	r
Piroxicam	117.365 ± 4.729	0.999
Surface deposit	138.122 ± 16.554	0.994

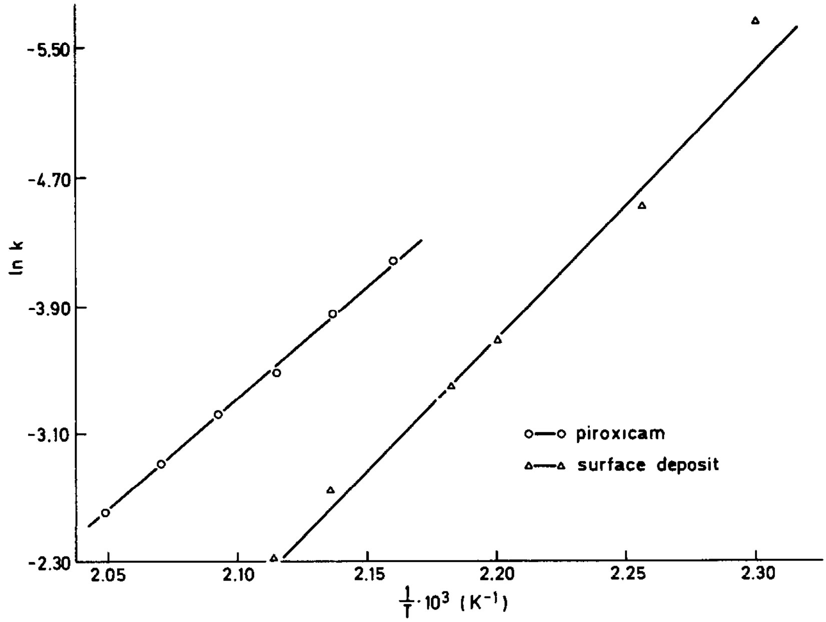

Fig. 6. Arrhenius-type plots for decomposition of micronized piroxicam and its surface deposit on Aerosil^R 380.

TABLE 7

Activation energies at different α values (according to Wiedemann) for isothermal decomposition of piroxicam and surface deposit

α	E (kJ mol^{-1})	
	Piroxicam	Surface deposit
0.2	153.55 ± 10.41 (0.998)	137.03 ± 38.28 (0.970)
0.3	146.20 ± 10.46 (0.998)	137.66 ± 31.46 (0.980)
0.4	140.33 ± 15.05 (0.996)	138.45 ± 25.10 (0.987)
0.5	135.64 ± 8.85 (0.998)	138.74 ± 22.83 (0.990)
0.6	130.58 ± 10.26 (0.998)	137.62 ± 21.03 (0.991)
0.7	120.31 ± 5.31 (0.999)	135.99 ± 19.23 (0.992)
0.8	109.68 ± 10.19 (0.997)	131.19 ± 18.50 (0.992)

Correlation coefficients in parentheses.

of the resulting plot allows E to be calculated (Table 6, Fig. 6). The activation energy for pure piroxicam and its surface deposit, calculated in this way, was tested by the Student t-distribution test. The difference between activation energies is significant at levels of significance $p = 0.10$.

The activation energy can also be determined even when the mechanism of the reaction is not known [8,9]. The relation between $\ln(d\alpha/dt)$ (α-const) and $1/T$ for a group of isotherms is linear. This relation is usually represented for the whole thermal decomposition, i.e. for different α values. E is then calculated for all α values. However, using this method the activation energy and the reaction mechanism can be tested. If E does not change with different α values, the reaction mechanism remains the same for the whole reaction. E is changed when the reaction mechanism is changed.

Therefore, it was determined whether pure piroxicam and the surface deposit decompose over one or several different mechanisms. At different α values (0.2, 0.3, 0.4, 0.5, 0.6, 0.7 and 0.8) $d\alpha/dt$ values were graphically determined, and the E values at the different α values were calculated (Table 7). E for pure piroxicam changes with different α values which confirms the statement that the reaction mechanism is different at different decomposition levels. The E for the surface deposit at all α values remains the same, in accordance with E values calculated using the linear law for the acceleratory part of the isothermal plots (Table 7).

By calculating the piroxicam molecule surface (using the CPK space-filling model), this surface was found to be much greater than the disposable surface of the carrier (i.e. Aerosil^{R} 380). Therefore, a multi-layer state is suggested which represents a homogeneous state: E is nearly constant over the whole α range. In contrast, the situation is totally different with pure micronized piroxicam. Compared to the surface deposit, E for micronized piroxicam was found to be greater at the beginning and much smaller at the end ($\alpha = 0.8$) of the decomposition.

The difference in state between the micronized piroxicam and the surface deposit was confirmed by DSC, as already mentioned, and also with X-ray diffraction and scanning electron microscopy [10].

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