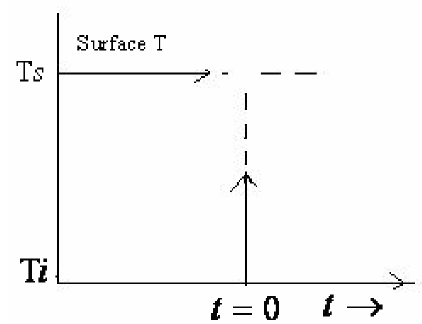
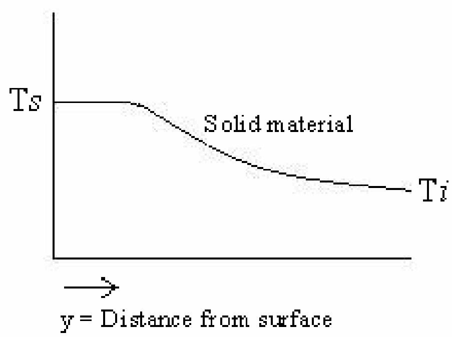
APPENDIX A: Formulae to calculate the heat transfer in a solid material.

Derived by Prof A. Bryson

These formulae relate the relationship between temperature in the furnace, time and depth of the heated samples. The transient energy transfer from a surface that is heated from T_s to T_i can be calculated as follows:





Heat flows from a hotter surface (T_s) to the colder interior (T_i) body. The rate of heat transfer depends on the temperature gradient and the thermal conductivity given by equation 1.

$$\frac{\partial T(y,t)}{\partial t} \approx \frac{\kappa}{\rho C_p} \frac{\partial^2 T}{\partial y^2}(y,t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots..$$

Cp = specific heat

ρ = density

κ =thermal conductivity

t = the time of exposure to heat and y = depth of heated sample.

$$\frac{\partial T(y,t)}{\partial t} \approx \alpha \frac{\partial^2 \mathrm{T}}{\partial y^2}(y,t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where $\alpha = \frac{\kappa}{\rho C_p}$ (thermal diffusivity)

- Initial conditions

$\mathrm{T}(y,0) = \mathrm{T}_i$

- Boundary condition 1

$\mathrm{T}(0,t) = \mathrm{T}_s$

- Boundary condition 2

$\mathrm{T}(\infty,t) = \mathrm{T}_i$

By making T dimensionless:

Let $\theta(y,t) = \frac{\mathrm{T}(y,t) - \mathrm{T}_i}{\mathrm{T}_s - \mathrm{T}_i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$

Where $\theta(y,t)$ = the heat conducted during a time t through a depth y.

$\frac{\partial \theta(y,t)}{\partial t} = \alpha \frac{\partial^2 \theta(y,t)}{\partial y^2}$ from equation (2).

Then $\theta(y,0) = 0$

$\theta(0,t) = 1$

$\theta(\infty,t) = 0$

This has a standard solution;

$$\theta(y,t) = 1 - erf\left(\frac{y}{\sqrt[2]{\alpha t}}\right)$$

where erf represents the error function.

However, heat transfer by convection (heat transferred by the circulation of air currents from one region to another) must contribute, which makes this relationship much more complex:

$$\theta(y,t) = 1 - erf\left(\frac{y}{\sqrt[2]{\alpha t}}\right) - \left[\exp\left(\frac{hy}{k} + \frac{h^2 \alpha t}{k^2}\right)\right]\left[1 - erf\left(\frac{y}{\sqrt[2]{\alpha t}} + \frac{h\sqrt{\alpha t}}{k}\right)\right],$$

h = 10W/m^{2}K (Boltzmann's constant)

APPENDIX B: Mass loss data from abrasion tests

Three samples were tested for each test condition (see tables 3.1 and 3.2).

B1: Effect of thermal shock temperature on abrasive wear

Table B1: Mass loss on samples of WC-12wt%Co without thermal shock.

	Sample 1		Sample 2		Sample3	
Time(sec)	Mass loss(g)	Cumulative mass loss(g)	Mass loss(g)	Cumulative mass loss(g)	Mass loss(g)	Cumulative mass loss(g)
0	0	0	0	0	0	0
7.2	0.004	0.004	0.003	0.003	0.003	0.003
14.4	0.002	0.006	0.002	0.005	0.003	0.006
21.6	0.001	0.007	0.002	0.007	0.002	0.008
28.8	0.001	0.008	0.001	0.008	0.001	0.009
36	0.001	0.009	0.001	0.009	0.001	0.01
43.2	0.001	0.01	0.001	0.01	0.001	0.011
50.4	0	0.01	0.001	0.011	0.001	0.012
57.6	0.001	0.011	0.001	0.012	0.001	0.013
64.8	0.001	0.012	0.001	0.013	0	0.013
72	0.001	0.013	0	0.013	0	0.013
79.2	0.001	0.014	0.001	0.014	0.001	0.014
86.4	0	0.014	0.001	0.015	0	0.014
93.6	0.001	0.015	0.001	0.016	0.001	0.015
100.8	0	0.015	0	0.016	0	0.015
108	0	0.015	0.001	0.017	0	0.015
115.2	0	0.015	0	0.017	0	0.015
122.4	0.001	0.016	0.001	0.018	0.001	0.016
129.6	0	0.016	0	0.018	0	0.016
136.8	0	0.016	0	0.018	0	0.016
144	0	0.016	0.001	0.019	0.001	0.017
151.2	0.001	0.017	0	0.019	0	0.017
158.4	0	0.017	0	0.019	0	0.017
165.6	0	0.017	0	0.019	0.001	0.018
172.8	0	0.017	0	0.019	0	0.018
180	0	0.017	0	0.019	0	0.018

Table B2: Mass loss after abrasive wear on samples subjected to 60 thermal shock cycles at 600℃.

Sample 1			Sample 2		Sample3	
Time(sec)	Mass loss(g)	Cumulative mass loss(g)	Mass loss(g)	Cumulative mass loss(g)	Mass loss(g)	Cumulative mass loss(g)
0	0	0	0	0	0	0
7.2	0.003	0.003	0.005	0.005	0.004	0.004
14.4	0.002	0.005	0.003	0.008	0.003	0.007
21.6	0.002	0.007	0.001	0.009	0.002	0.009
28.8	0.001	0.008	0.002	0.011	0.001	0.01
36	0.001	0.009	0	0.011	0.001	0.011
43.2	0.001	0.01	0.002	0.013	0.001	0.012
50.4	0	0.01	0.001	0.014	0	0.012
57.6	0.002	0.012	0.001	0.015	0.001	0.013
64.8	0	0.012	0.001	0.016	0.001	0.014
72	0.001	0.013	0	0.016	0	0.014
79.2	0	0.013	0.001	0.017	0	0.014
86.4	0.001	0.014	0	0.017	0.001	0.015
93.6	0	0.014	0	0.017	0	0.015
100.8	0	0.014	0.001	0.018	0	0.015
108	0	0.014	0.001	0.019	0.001	0.016
115.2	0.001	0.015	0	0.019	0	0.016
122.4	0.001	0.016	0	0.019	0	0.016
129.6	0	0.016	0	0.019	0.001	0.017
136.8	0	0.016	0	0.019	0	0.017
144	0	0.016	0.001	0.02	0	0.017
151.2	0.001	0.017	0	0.02	0.001	0.018
158.4	0	0.017	0	0.02	0	0.018
165.6	0	0.017	0.001	0.021	0	0.018
172.8	0.001	0.018	0	0.021	0.001	0.019
180	0	0.018	0	0.021	0	0.019

Table B3: Mass loss after abrasive wear on samples subjected to 60 thermal shock cycles at 800℃.

Sample 1			Sample 2		Sample3	
Time(sec)	Mass loss(g)	Cumulative mass loss(g)	Mass loss(g)	Cumulative mass loss(g)	Mass loss(g)	Cumulative mass loss(g)
0	0	0	0	0	0	0
7.2	0.003	0.003	0.005	0.005	0.005	0.005
14.4	0.003	0.006	0.002	0.007	0.004	0.009
21.6	0.001	0.007	0.001	0.008	0.002	0.011
28.8	0.001	0.008	0.001	0.009	0.001	0.012
36	0.001	0.009	0.001	0.01	0.001	0.013
43.2	0	0.009	0.001	0.011	0.001	0.014
50.4	0.002	0.011	0.001	0.012	0.001	0.015
57.6	0.001	0.012	0.001	0.013	0	0.015
64.8	0	0.012	0	0.013	0.001	0.016
72	0.001	0.013	0.001	0.014	0	0.016
79.2	0.001	0.014	0	0.014	0.001	0.017
86.4	0.001	0.015	0.001	0.015	0	0.017
93.6	0.001	0.016	0	0.015	0	0.017
100.8	0	0.016	0	0.015	0.001	0.018
108	0.001	0.017	0.001	0.016	0	0.018
115.2	0.001	0.018	0	0.016	0.001	0.019
122.4	0	0.018	0	0.016	0	0.019
129.6	0.001	0.019	0.001	0.017	0	0.019
136.8	0	0.019	0	0.017	0	0.019
144	0.001	0.02	0	0.017	0.001	0.02
151.2	0	0.02	0	0.017	0	0.02
158.4	0.001	0.021	0	0.017	0	0.02
165.6	0	0.021	0.001	0.018	0.001	0.021
172.8	0	0.021	0	0.018	0	0.021
180	0	0.021	0	0.018	0	0.021

Table B4: Mass loss after abrasive wear on samples subjected to 60 thermal shock cycles at 1000℃.

Sample 1			Sample 2		Sample3	
Time(sec)	Mass loss(g)	Cumulative mass loss(g)	Mass loss(g)	Cumulative mass loss(g)	Mass loss(g)	Cumulative mass loss(g)
0	0	0	0	0	0	0
7.2	0.005	0.005	0.005	0.005	0.007	0.007
14.4	0.002	0.007	0.003	0.008	0.003	0.01
21.6	0.001	0.008	0.001	0.009	0.001	0.011
28.8	0.001	0.009	0.002	0.011	0.001	0.012
36	0.001	0.01	0.001	0.012	0.002	0.014
43.2	0.002	0.012	0.001	0.013	0.001	0.015
50.4	0	0.012	0.001	0.014	0.001	0.016
57.6	0.001	0.013	0.001	0.015	0.001	0.017
64.8	0.001	0.014	0.001	0.016	0.001	0.018
72	0.001	0.015	0.001	0.017	0.001	0.019
79.2	0	0.015	0.001	0.018	0	0.019
86.4	0	0.015	0.001	0.019	0.001	0.02
93.6	0.001	0.016	0.001	0.02	0	0.02
100.8	0	0.016	0	0.02	0.001	0.021
108	0	0.016	0	0.02	0	0.021
115.2	0.001	0.017	0	0.02	0.001	0.022
122.4	0	0.017	0.001	0.021	0	0.022
129.6	0	0.017	0	0.021	0	0.022
136.8	0	0.017	0	0.021	0.001	0.023
144	0.001	0.018	0	0.021	0	0.023
151.2	0.001	0.019	0.001	0.022	0.001	0.024
158.4	0	0.019	0	0.022	0	0.024
165.6	0	0.019	0	0.022	0	0.024
172.8	0	0.019	0	0.022	0	0.024
180	0	0.019	0.001	0.023	0	0.024

B2: Effect of thermal shock cycles on abrasive wear

Table B5: Mass loss after abrasive wear on samples subjected to 60 thermal shock cycles at 800℃.

	Sample 1		Sample 2		Sample3	
Time(sec)	Mass loss(g)	Cumulative mass loss(g)	Mass loss(g)	Cumulative mass loss(g)	Mass loss(g)	Cumulative mass loss(g)
0	0	0	0	0	0	0
7.2	0.003	0.003	0.005	0.005	0.005	0.005
14.4	0.003	0.006	0.002	0.007	0.004	0.009
21.6	0.001	0.007	0.001	0.008	0.002	0.011
28.8	0.001	0.008	0.001	0.009	0.001	0.012
36	0.001	0.009	0.001	0.01	0.001	0.013
43.2	0	0.009	0.001	0.011	0.001	0.014
50.4	0.002	0.011	0.001	0.012	0.001	0.015
57.6	0.001	0.012	0.001	0.013	0	0.015
64.8	0	0.012	0	0.013	0.001	0.016
72	0.001	0.013	0.001	0.014	0	0.016
79.2	0.001	0.014	0	0.014	0.001	0.017
86.4	0.001	0.015	0.001	0.015	0	0.017
93.6	0.001	0.016	0	0.015	0	0.017
100.8	0	0.016	0	0.015	0.001	0.018
108	0.001	0.017	0.001	0.016	0	0.018
115.2	0.001	0.018	0	0.016	0.001	0.019
122.4	0	0.018	0	0.016	0	0.019
129.6	0.001	0.019	0.001	0.017	0	0.019
136.8	0	0.019	0	0.017	0	0.019
144	0.001	0.02	0	0.017	0.001	0.02
151.2	0	0.02	0	0.017	0	0.02
158.4	0.001	0.021	0	0.017	0	0.02
165.6	0	0.021	0.001	0.018	0.001	0.021
172.8	0	0.021	0	0.018	0	0.021
180	0	0.021	0	0.018	0	0.021

Table B6: Mass loss after abrasive wear on samples subjected to 80 thermal shock cycles at 800℃.

Sample 1			Sample 2		Sample3	
Time(sec)	Mass loss(g)	Cumulative mass loss(g)	Mass loss(g)	Cumulative mass loss(g)	Mass loss(g)	Cumulative mass loss(g)
0	0	0	0	0	0	0
7.2	0.005	0.005	0.004	0.004	0.004	0.004
14.4	0.004	0.009	0.002	0.006	0.002	0.006
21.6	0.002	0.011	0.001	0.007	0.001	0.007
28.8	0.001	0.012	0.001	0.008	0.001	0.008
36	0.001	0.013	0	0.008	0	0.008
43.2	0.001	0.014	0.001	0.009	0.001	0.009
50.4	0.001	0.015	0	0.009	0.001	0.01
57.6	0	0.015	0.002	0.011	0.001	0.011
64.8	0.001	0.016	0.001	0.012	0	0.011
72	0.001	0.017	0	0.012	0.001	0.012
79.2	0.001	0.018	0.001	0.013	0	0.012
86.4	0.001	0.019	0.001	0.014	0	0.012
93.6	0	0.019	0	0.014	0.001	0.013
100.8	0.001	0.02	0.001	0.015	0	0.013
108	0	0.02	0	0.015	0	0.013
115.2	0	0.02	0	0.015	0	0.013
122.4	0	0.02	0.001	0.016	0.001	0.014
129.6	0.001	0.021	0	0.016	0	0.014
136.8	0	0.021	0	0.016	0	0.014
144	0	0.021	0.001	0.017	0	0.014
151.2	0.001	0.022	0	0.017	0.001	0.015
158.4	0	0.022	0	0.017	0	0.015
165.6	0	0.022	0.001	0.018	0	0.015
172.8	0.001	0.023	0	0.018	0.001	0.016
180	0	0.023	0	0.018	0	0.016

Table B7: Mass loss after abrasive wear on samples subjected to 100 thermal shock cycles at 800℃.

Sample 1			Sample 2		Sample3	
Time(sec)	Mass loss(g)	Cumulative mass loss(g)	Mass loss(g)	Cumulative mass loss(g)	Mass loss(g)	Cumulative mass loss(g)
0	0	0	0	0	0	0
7.2	0.005	0.005	0.004	0.004	0.004	0.004
14.4	0.002	0.007	0.003	0.007	0.003	0.007
21.6	0.002	0.009	0.002	0.009	0.002	0.009
28.8	0.002	0.011	0.001	0.01	0.001	0.01
36	0.002	0.013	0	0.01	0.001	0.011
43.2	0.001	0.014	0.001	0.011	0.001	0.012
50.4	0.001	0.015	0	0.011	0	0.012
57.6	0	0.015	0.001	0.012	0.001	0.013
64.8	0.001	0.016	0	0.012	0.001	0.014
72	0	0.016	0.001	0.013	0.001	0.015
79.2	0.001	0.017	0	0.013	0.001	0.016
86.4	0	0.017	0	0.013	0.001	0.017
93.6	0	0.017	0.001	0.014	0	0.017
100.8	0.001	0.018	0.001	0.015	0	0.017
108	0	0.018	0	0.015	0.001	0.018
115.2	0.001	0.019	0.001	0.016	0	0.018
122.4	0.001	0.02	0.001	0.017	0	0.018
129.6	0	0.02	0	0.017	0.001	0.019
136.8	0	0.02	0	0.017	0	0.019
144	0	0.02	0.001	0.018	0.001	0.02
151.2	0.001	0.021	0	0.018	0	0.02
158.4	0	0.021	0	0.018	0	0.02
165.6	0	0.021	0	0.018	0	0.02
172.8	0	0.021	0.001	0.019	0.001	0.021
180	0	0.021	0	0.019	0	0.021

APPENDIX C: XRD data for sample subjected to 60 thermal shock cycles at 1000°C

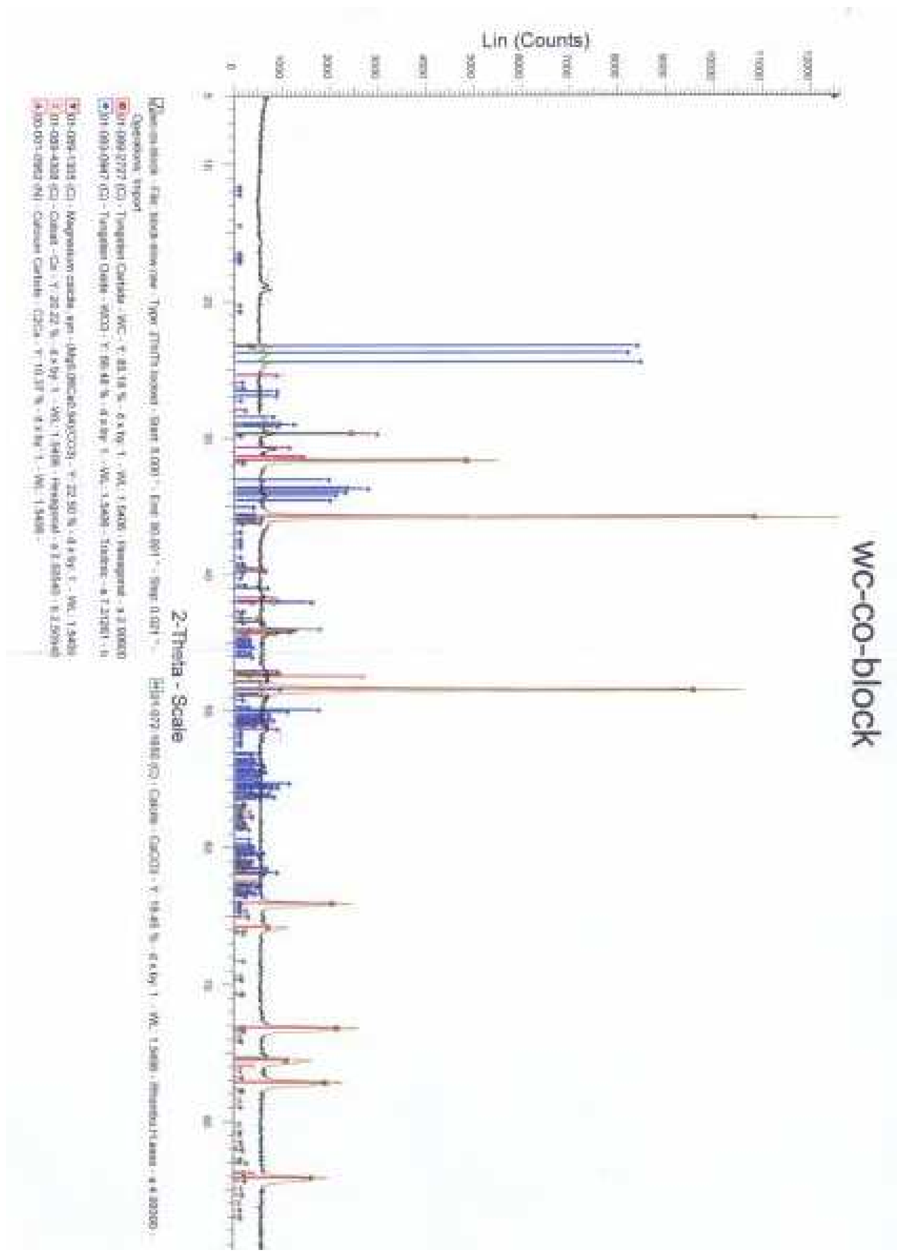


Figure C1: XRD pattern for WC-12wt%Co after 60 thermal shock cycles at 1000℃.

The X-ray diffraction data (Pattern - Figure C1) was collected using a Bruker AXS D8 equipped with a V Åntec-1 detector and using Cu-K_α radiation (40Kv, 40mA). Data was acquired in the ranges 5 to 90°C steps, using a scan speed resulting in an equivalent counting tie of 14.7s per step. This XRD analysis was done to determine the changes in phase compositions after thermal shock

Table C1: Peak list of WC, reference code: 01-072-0097.

No.	h	k	l	d [A]	2Theta[deg]	I [%]
1	0	0	1	2.83660	31.514	44.0
2	1	0	0	2.51710	35.640	100.0
3	1	0	1	1.88273	48.302	83.2
4	1	1	0	1.45325	64.018	15.3
5	0	0	2	1.41830	65.792	4.6
6	1	1	1	1.29339	73.106	15.2
7	2	0	0	1.25855	75.476	7.1
8	1	0	2	1.23565	77.129	13.2
9	2	0	1	1.15040	84.071	10.5

Table C2: Peak list of Co, reference code: 01-089-4308.

h	k	l	d [A]	2Theta[deg]	I [%]
1	0	0	2.16974	41.589	27.0
0	0	2	2.04465	44.264	28.6
1	0	1	1.91666	47.394	100.0
1	0	2	1.48804	62.351	11.4
1	1	0	1.25270	75.891	9.7
1	0	3	1.15423	83.729	9.8

Table C3: Peak list of WO_3, reference code: 01-075-2072.

h	k	l	d [A]	2Theta[deg]	I [%]
1	1	0	5.22190	16.966	0.1
0	0	1	3.82400	23.242	100.0
0	2	0	3.75050	23.704	99.1
1	0	0	3.63700	24.455	95.9
0	1	1	3.40683	26.136	13.7
1	2	0	3.33348	26.721	8.3
0	2	1	2.67761	33.438	43.7
2	0	1	2.63377	34.012	36.1
2	2	0	2.61095	34.318	44.7

1	2	1	2.51208	35.714	10.2
2	1	1	2.48773	36.075	9.7
2	2	1	2.15539	41.879	22.4
0	0	2	1.91200	47.516	11.5
0	4	0	1.87525	48.507	11.3
0	1	2	1.85276	49.134	7.0
4	0	0	1.81850	50.123	14.1
1	4	0	1.81588	50.200	11.5
3	2	-1	1.79652	50.779	2.7
0	2	2	1.70342	53.771	9.7
2	0	2	1.69153	54.180	7.6
0	4	1	1.68370	54.452	10.9
2	4	0	1.66674	55.053	10.2
2	1	2	1.65168	55.598	7.1
4	0	-1	1.64148	55.974	12.2
4	2	0	1.63630	56.167	17.6