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Background

A recent process development test relating to carburizing illustrated the need to better understand the effect of surface emissivity and the proper use of dummy thermocouple test blocks.

The testing involved carburizing areas of a partially copper plated alloy steel part. The copper plating covered areas of the part that were not to be carburized. Since the configuration of the part made it impossible to place a thermocouple within the part, a dummy test block made of carbon steel with the approximate same cross-section was used for the process thermocouple without proper consideration of the surface condition of the test block.

Using the test block as the control, carburizing was initiated at the proper temperature based on the test block having reached that temperature.

At the completion of the test, the part was examined for carburizing results and found in the non-copper plated areas, the depth of the carburized case to be shallow. This indicated that the cycle performed did not initially hold the part long enough at the correct temperature prior to carburizing. This resulted in the conclusion that when using dummy test blocks for controlling process times and temperatures, many factors must be considered including surface emissivity.

Thus the following document highlighting emissivity and test block considerations follows.

A) Part Surface Emissivity

The ability of a surface to emit and absorb radiation is defined by the term ***emissivity.***

At any given temperature, the <u>emissivity of a body (or surface) equals its absorptivity</u>.

Vacuum furnaces provide heat to a workload via radiation from the furnace heating elements. In practice, most materials and surfaces are “gray bodies” having an emissivity factor less than 1.0. For practical purposes, it can be assumed that a good reflector is usually a poor absorber.

The surface condition of a material can greatly affect its ability to absorb radiant energy. The same material with equal cross-section and mass can take as long as twice the time to reach final temperature if surface conditions vary. This is illustrated in the following Chart 1 for various materials and their respective surface condition.

Approximate Emissivity

Metals	***Polished***	***Rough***	***Oxidized***
Aluminum	0.04	0.055	0.11-0.19
Brass	0.03	0.06-0.2	0.60
Chrome	0.08	---	0.17
Copper	0.018-0.02	---	0.57
Gold	0.018-0.035	---	---
Steel	0.12-0.40	0.75	0.80-0.95
Stainless	0.11	0.57	0.80-0.95
Lead	0.057-0.075	0.28	0.63
Nickel	0.045-0.087	---	0.37-0.48
Silver	0.02-0.035	---	---
Tin	0.04-0.065	---	---
Zinc	0.045-0.053	---	0.11
Galvanized Iron	0.228	---	0.276

Chart 1

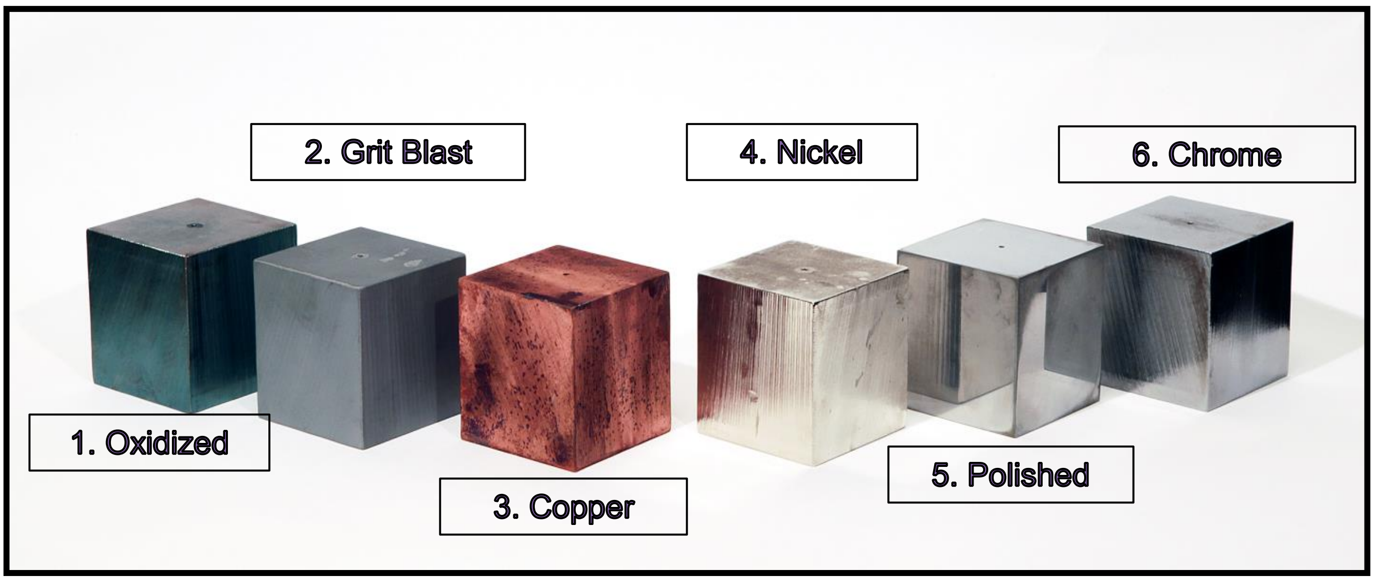
In vacuum furnace heating, several complex factors affect the overall time it takes for materials to reach uniform process temperature including load weight, part cross-section, and heating rate. As stated above, emissivity is another important factor directly affecting the heat absorption capability of the material being processed.

Knowing the emissivity of a material is most critical when using separate dummy thermocouple blocks to simulate actual workload temperature. Not only must the thermocouple block represent the average cross-section of the parts, but it must also represent the surface condition (color, roughness, or amount of oxidation) of the material being processed.

To illustrate the importance of the emissivity factor in load heating and dummy thermocouple blocks, we prepared six samples of carbon steel blocks and altered the surface to prepare them for testing.

The blocks were all carbon steel measuring 2.50” W x 2.50” L x 2.50” H with a .093” hole drilled at the center 1.25” deep for thermocouple insertion. The surfaces of the blocks were modified as follows:

1) Block 1 – Carbon Steel Oxidized
2) Block 2 – Carbon Steel Grit Blasted
3) Block 3 – Carbon Steel Copper Plated
4) Block 4 – Carbon Steel Nickel Plated
5) Block 5 – Carbon Steel Polished Shiny
6) Block 6 – Carbon Steel Chrome Plated



The blocks were then placed in a vacuum furnace set to run the following cycle:

a) Load dummy blocks into a work basket with generous spacing between blocks and relatively equal distance from the heating elements.
b) Insert T/Cs into each block with identification for each test sample.
c) Pump furnace down to initial vacuum of less than $1x10^{-3}$ Torr.
d) Heat Furnace to 1000^oF at 15^oF per minute.
e) Hold at 1000^oF until all blocks are within 10 ^oF of set point and then hold 15 minutes.
f) Heat furnace to 1700^oF at 15^oF per minute.
g) Hold at 1700^oF until all blocks are within 10 ^oF of set point and then hold 15 minutes.
h) Cool load and furnace back to unloading temperature.

Test results are shown in the following curve:

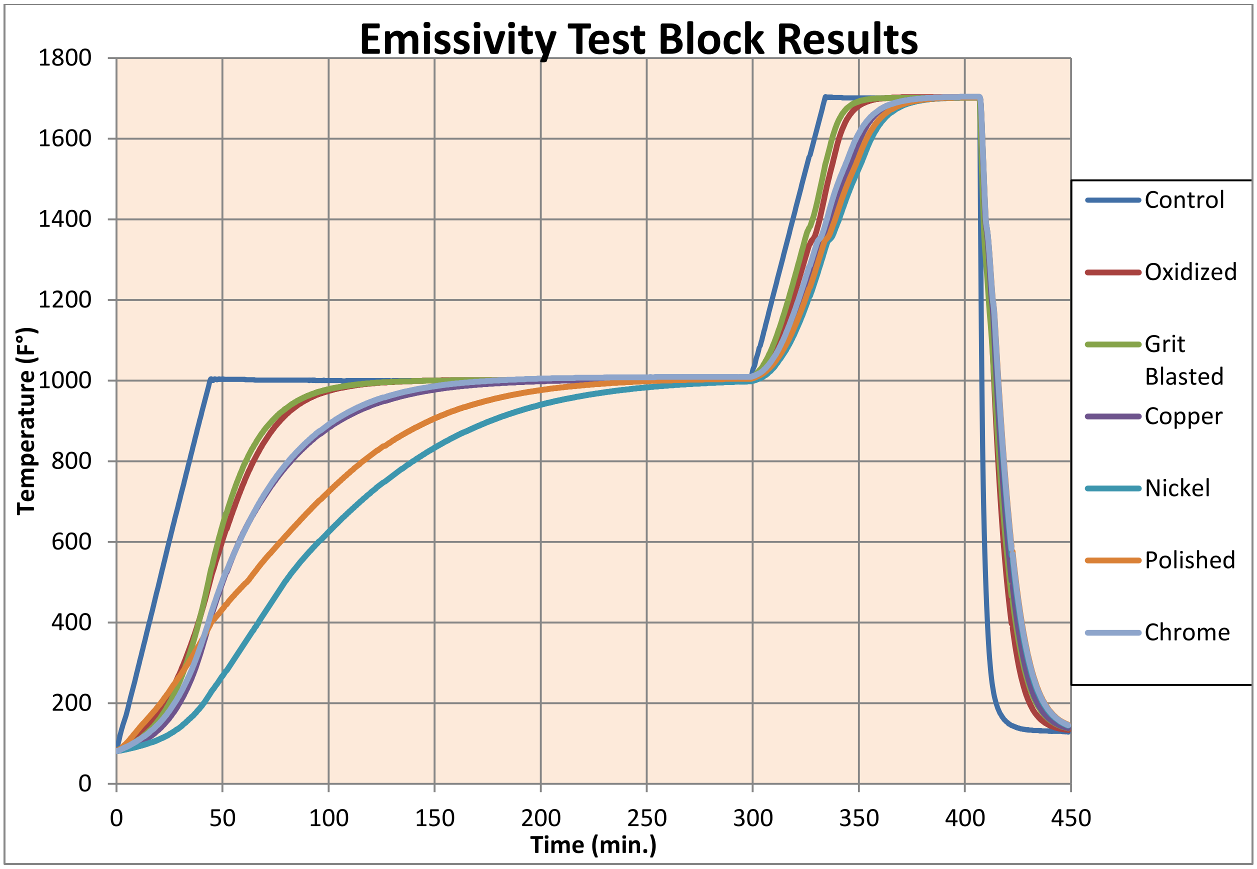


Figure 1 - Emissivity Surface Modification Test

The curves above in Figure 1 illustrate the important part that emissivity or absorptivity plays relating to heating materials in a vacuum furnace.

Summarizing the above, we have the following Chart 2

Test Block Surface Condition – 2.5" Cubes Carbon Steel	*Approximate Emissivity Value*	*Heating Time to 1000^{o}F (Minutes)*	*Heating Time From 1000^{o}F to 1700^{o}F (Minutes)*	*Total Heating Time (Minutes)*
Grit Blasted	0.75 - 0.80	111	49	160
Oxidized	0.80 – 0.95	114	54	168
Chrome Plated	0.20 – 0.40	152	68	220
Copper Plated	0.04 – 0.57	168	68	236
Polished	0.12 – 0.40	241	74	315
Nickel Plated	0.045 – 0.08	264	75	339

Chart 2

The chart illustrates how the same sized block of carbon steel can take as long as twice the time to heat to temperature depending on how the surface is altered or modified. The approximate emissivity value of the surface condition is closely reflected in the relative heating times.

This can now allow us to predict the relative heating rates of the different surface conditions and their respective emissivity values. This is shown in the next figure.

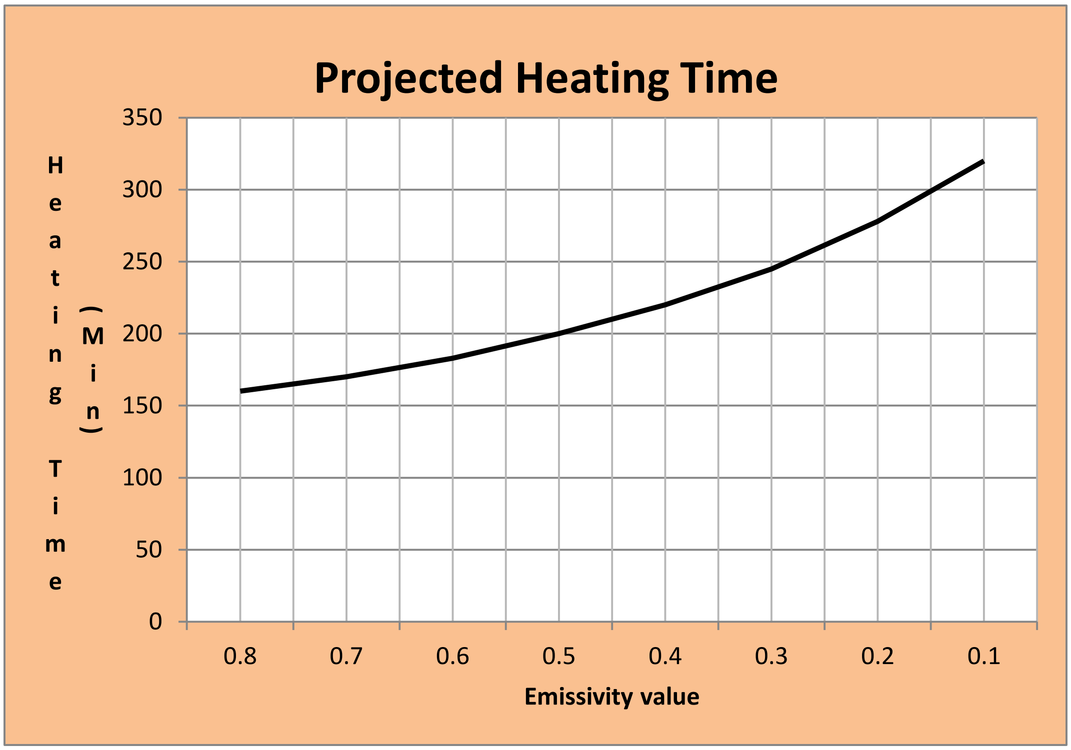


Figure 2 – Heating Rates Based on Emissivity

B) Test Block Mass and Cross-section

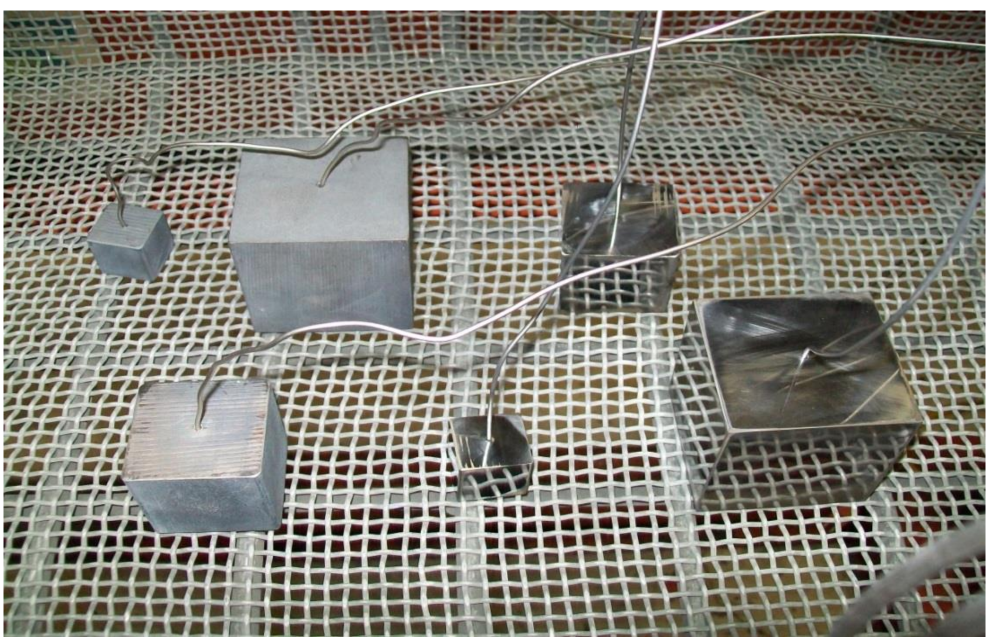
To further demonstrate the importance of correct cross-section and surface condition in thermocouple test blocks, we prepared a second series of test blocks.

We took pairs of three sizes of blocks and oxidized one and polished the other. We ended up with the following samples:

1) Block 1 – 1” Cube Oxidized
2) Block 2 – 1” Cube Polished
3) Block 3 – 1.75” Cube Oxidized
4) Block 4 – 1.75” Cube Polished
5) Block 5 – 2.5” Cube Oxidized
6) Block 6 – 2.5” Cube Polished

The blocks were then placed in a vacuum furnace set to run the following cycle:

a) Load dummy blocks into a work basket with generous spacing between blocks and relative equal distance from the heating elements.
b) Insert T/Cs within each block with identification for each test sample.
c) Pump furnace down to initial vacuum of less than $1x10^{-3}$ Torr.
d) Heat Furnace to 1150^{o}F at 15^{o}F per minute.
e) Hold at 1150^{o}F until all blocks are within 10 ^{o}F of set point and then hold 15 minutes.
f) Heat furnace to 1700^{o}F at 15^{o}F per minute.
g) Hold at 1700^{o}F until all blocks are within 10 ^{o}F of set point and then hold 15 minutes.
h) Cool load and furnace back to unloading temperature.



Results of our testing are shown in the following ***Figure 3***:

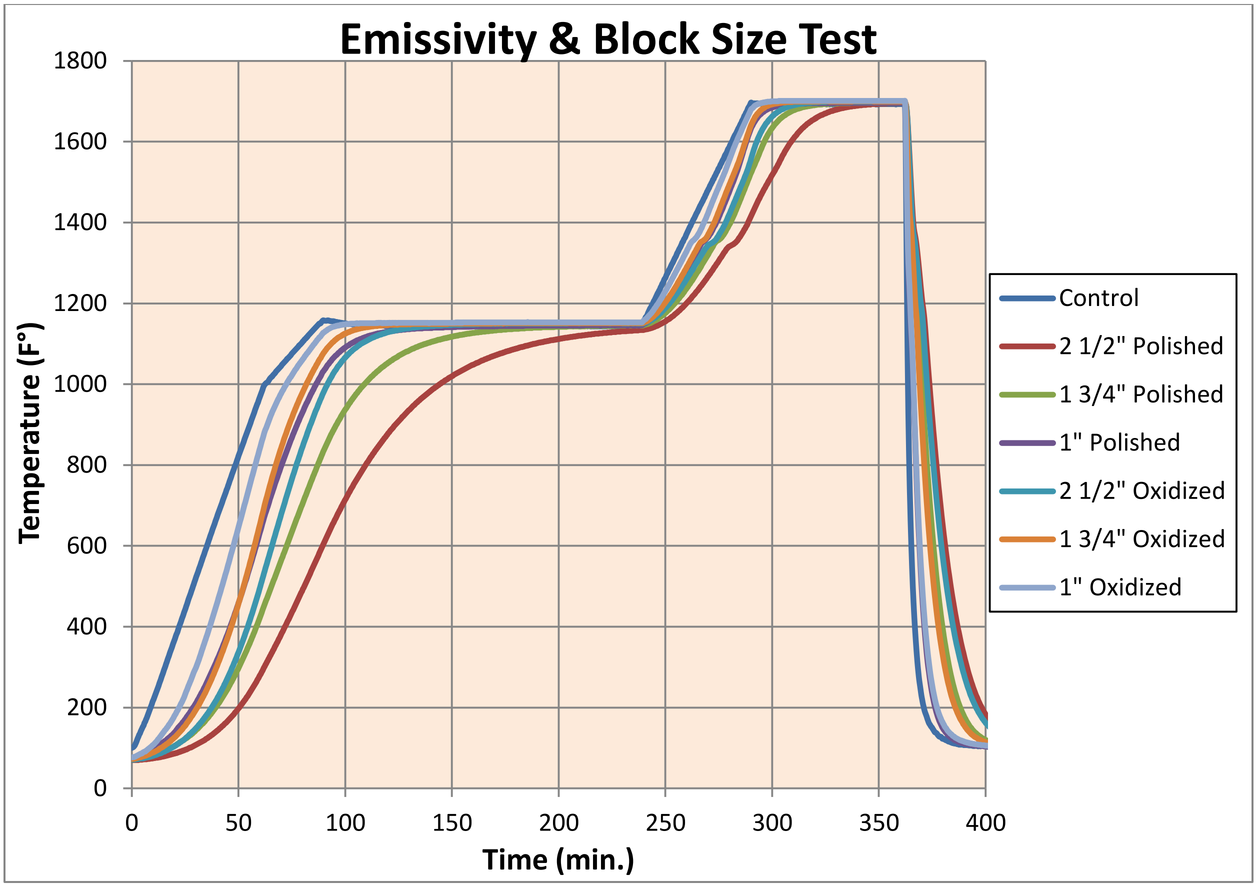


Figure 2 - Varying Size Block Heating Rates

Summarizing the results, we have the following Chart 3:

Test Block	***Approximate Emissivity Value***	***Heating Time to 1000°F (Minutes)***	***Heating Time From 1150°F to 1700°F (Minutes)***	***Total Heating Time (Minutes)***
1) 1"Cube Oxidized	0.80 – 0.95	68	39	107
2) 1.75"Cube Oxidized	0.80 – 0.95	79	46	125
3) 2.5" Cube Oxidized	0.80 – 0.95	98	48	146
4) 1" Cube Polished	0.12 – 0.40	100	53	153
5) 1.75" Cube Polished	0.12 – 0.40	135	55	180
6) 2.5" Cube polished	0.12 – 0.40	166	73	239

Chart 3

Chart 3 further emphasizes the critical consideration that must be given to thermocouple test blocks regarding mass, cross-section and surface condition. It is interesting that a 1” polished cube of carbon steel took longer to heat to temperature than a 2.5” oxidized cube of carbon steel.

C) Summary and Conclusions:

1) Radiation heating of materials in a vacuum furnace is greatly affected by the material ***emissivity*** and ***absorptivity***.
2) Bright and polished materials heat much slower than dull and dark surface materials.
3) The surface roughness of the material will affect heating rate. Rough surfaces heat faster than smooth, reflective surfaces.
4) When using thermocouple blocks to simulate actual load parts, not only must the material and cross-section be similar, but also the surface condition (color and texture) must be the same.
5) Thermocouple test blocks should be periodically re-conditioned to maintain proper surface smoothness and appearance.
6) One load of material, with a particular surface condition, compared with a load of the same material with another surface condition, could take as much as twice as long to reach the desired temperature.

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