

Stress and Strain in Enamel-Steel Composites: A Practical Viewpoint

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Summary

Enamels applied to steel have characteristics similar to bi-metallic strips. The stresses that are induced during the firing have a very practical value and can be beneficial to the after fired strength of the enamelled article. Understanding the limitations of the strains and stresses in enamels will aid in controlling the movement of parts that are exposed to high temperatures such as ovens and range tops.

Summary of the Enamel-Steel Characteristics

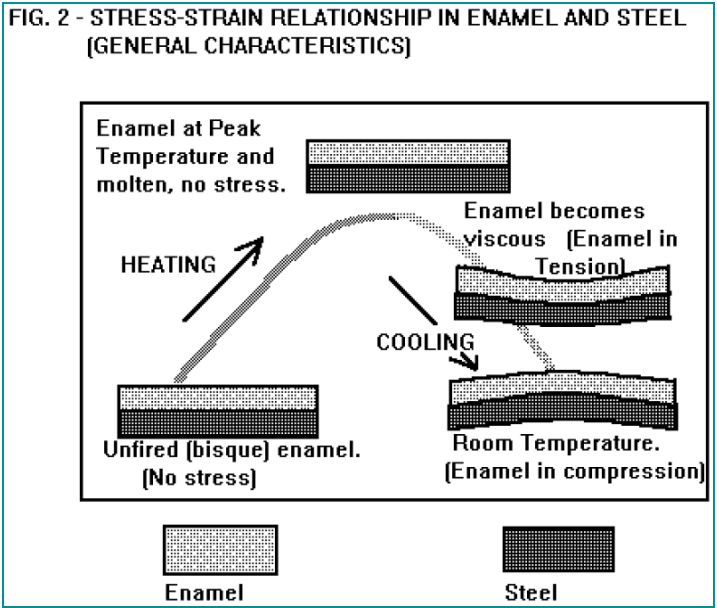
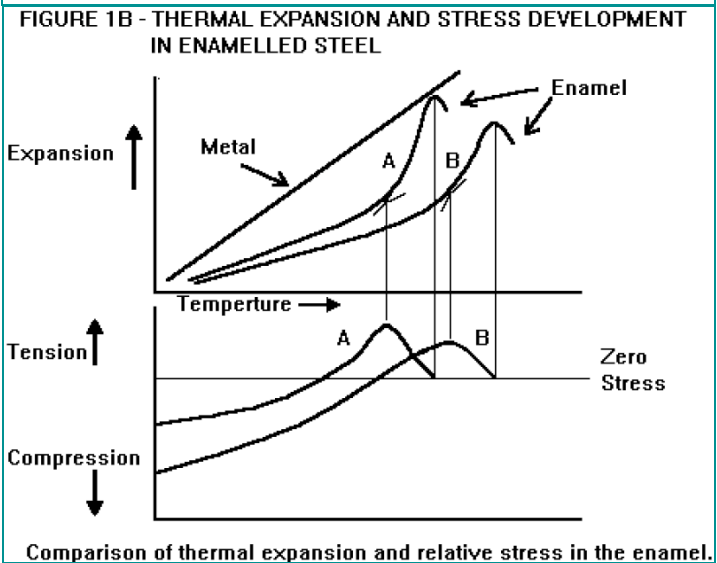
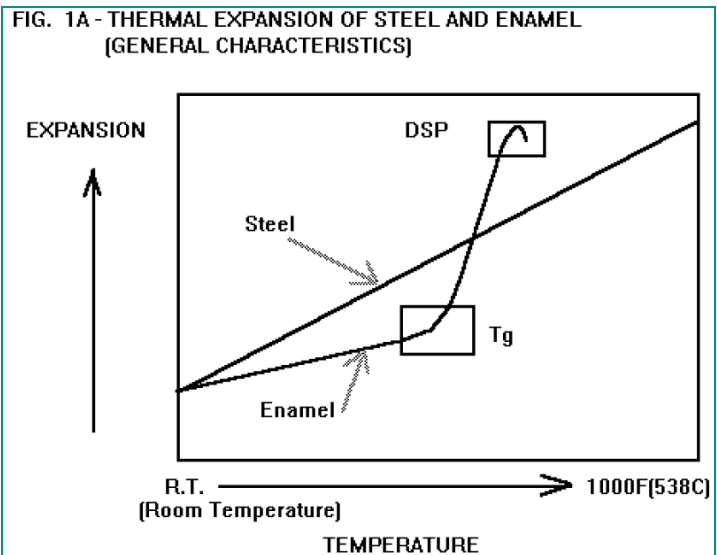
Porcelain enamel is a low temperature glass which is fired onto steel. The resultant composite system has unique characteristics which have a strong influence on its use properties. The enamel may be applied as either wet or dry powder systems onto prepared steel. Today, the steel is usually degreased and dried. The enamel layer will fuse at a relatively low temperature in the firing cycle to seal the surface of the metal to retard oxidation and then flow to form a uniform film on the metal substrate. During heating of the enamel-steel combination, the system is not under stress up to the point of peak fire¹. As the fused glass and metal start to cool, the different thermal expansions of the enamel and the steel now become important in developing the fired characteristics. The steel expands and contracts at a uniform rate within the range of the firing. The enamel will have different expansion and contraction rates as compared to the steel.

These differences are illustrated in Figures 1A and 1B.

From the dilatometric softening point (DSP) to the glass transition temperature (T_g) the enamel has one rate of expansion or contraction which is higher than that of the steel. Below the T_g, the enamel will contract at a slower rate than that of the steel.

Additionally, the glass will change drastically in viscosity as it goes through different temperature². At the DSP, the glass is very soft and any stresses are immediately relieved. However, as the glass cools, it becomes more viscous (stiffer) and the ability to relieve stresses or relax is much more difficult and slow.

Additional cooling will eventually cause the glass viscosity to rise to such a level that it will essentially be solid for practical purposes and stresses will not be relieved. Since the steel contracts at a uniform rate throughout the temperatures used in enamelling, on cooling it will keep shrinking at a constant rate. This shrinkage will interact with the varying rates of enamel contraction and make the enamelled article change in flexing direction as it cools. At room temperature, the steel will have shrunk more than the enamel and will cause the composite coating to bow as shown in Figure 2.



This indicates residual compressive stresses in the enamel which impart strength as the compression has to be overcome to crack the enamel.

Varying rates of cooling will change the amount of compression in the glass and affect the state of stress in the composite.

Review of Pyrolytic Systems

A. Initial Processing (In Plant)

Processing of parts once they are fabricated (raw steel) with the right enamel thickness is important as areas which are too thick or too thin develop a number of problems. Thick coatings are prone to chipping as well as distortion of the metal. Thin areas will show burn-off and possibly other defects such as "shiner scale". Handling of the parts after enamelling has to be done carefully since mechanical stresses can cause the enamel to crack and subsequently show defects in use. These stress cracks are not readily observed

unless the unit is highlighted in some way. Statically applying a very light coating of charged particles ("Stati-fluxing") will allow the observation of cracks that may have developed. Often, stress cracking is found around mounting points of various pieces of an oven and areas that have been mechanically twisted.

Controlled compressive stresses in the enameled part of the composite are desirable for use applications since glass is about 10 times stronger in compression than tension.

B. Testing

1. Life Testing

Life tests of pyrolytic ovens usually involve heating them to the self-cleaning temperature on a repetitive schedule that accelerates the aging of the oven. Factors which are important in the life test are the [1] peak temperature of the oven (usually the geometric center of the oven), [2] the rate of heating including the initial heat up, [3] the placement of the temperature sensor, and [4] the type of enamel. Ideally, a low glass transition temperature enamels tend to promote a greater degree of bubble migration and change in color with exposure to the peak cleaning temperatures. Copperheading which progresses to surface blemishes also occurs.

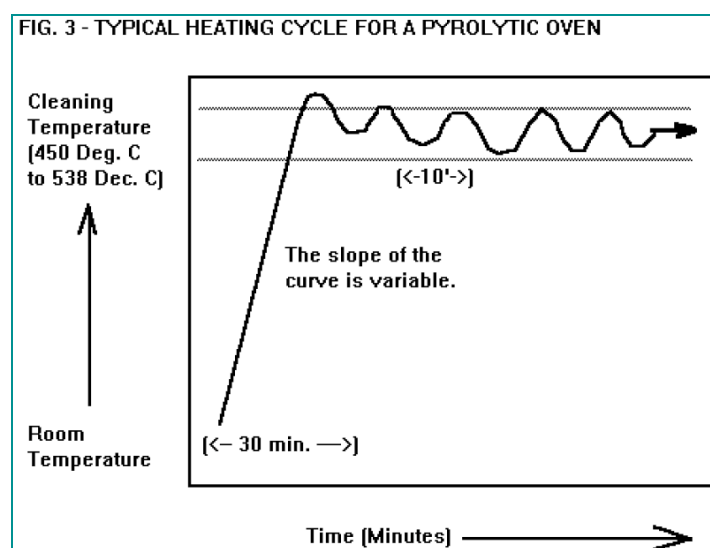


Figure 3 illustrates the type of heating pattern that is typical of a pyrolytic oven when it is heated to the cleaning temperature. The peak heating temperatures and heating

rates for gas and electric ovens are very similar. Life testing is usually measured in cycles per year or normal use, about 10 to 12 cycles for each year.

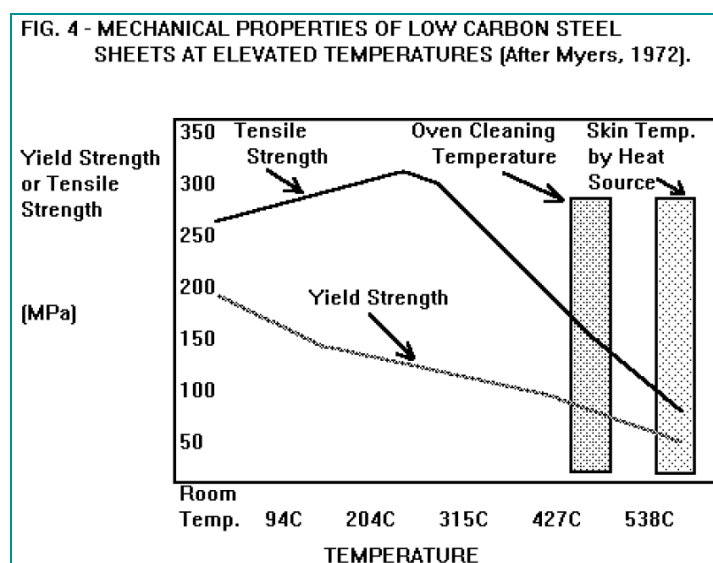
2. Cleanability

Cleanability of the enamel surface is primarily dependent on its acid resistance. A good acid resistant system (PEI Class A) is necessary to achieve good soil resistance. The types of soils vary with individual manufacturers regarding their experience and customer concerns. The AHAM soil as well as individual materials may be tested at pyrolytic cleaning temperatures followed by an evaluation of the results. The surface of the enamel after the cleaning test is evaluated qualitatively. In some cases, the soil will etch the surface of the enamel reduce the gloss which is seen as a residue on the surface. Multiple cycles may be part of the testing regime.

3. Examination of Cleaning Test Cycle

It has been found that cracking in pyrolytic enamel systems occurs on the first cycle and the cracks are normally tension cracks. A single broil cycle may also cause an enamel coating to crack.

Figure 4 illustrates the effect of temperature on yield strength and tensile strength of low carbon steel at elevated temperatures³. The steel becomes weaker at temperatures above 700 deg. F. (371 deg. C.). Cracking of the enamel in a constrained situation has been observed at 850 deg. F. (454 deg. C.). These cracks may not be visible except with a microscope or by applying a charge particle layer to highlight them. If there is a long lag (response time) between the time of heating and the temperature achieved, more energy will be put into the oven and greater stresses will be induced. Minimizing the power cycle time (on/off) and duration will lower the stress on the enamel layer.



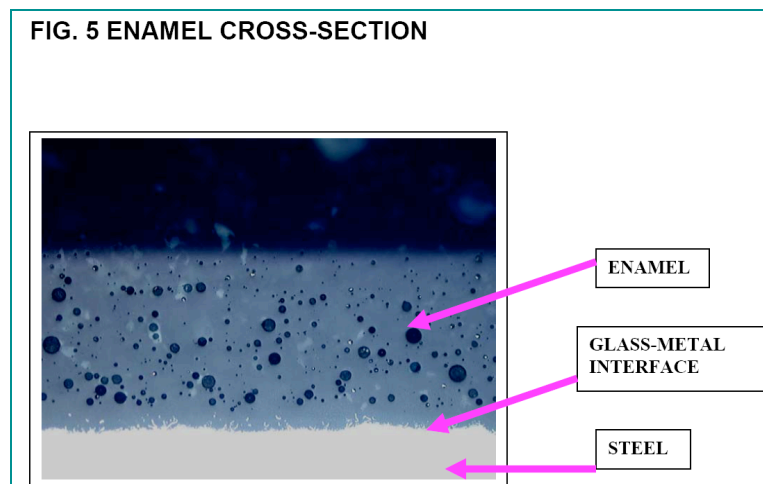
Enamel Characteristics

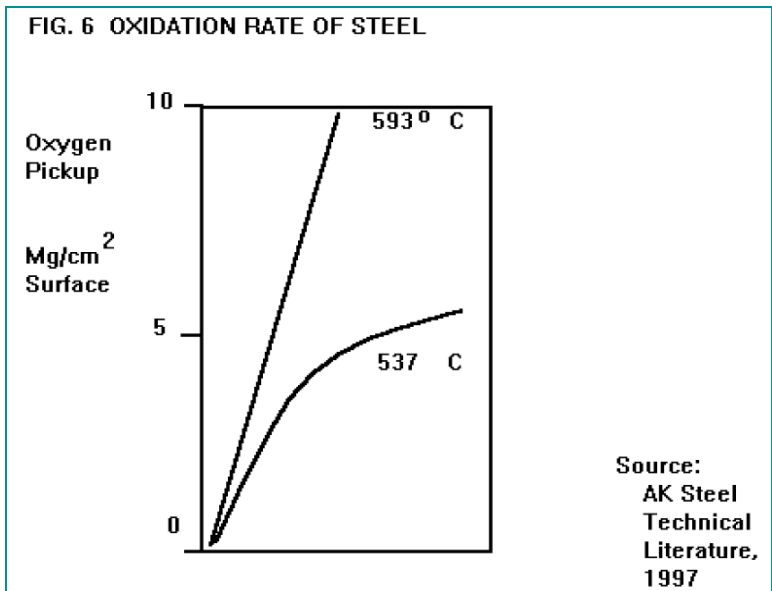
A. Interface (Enamel-Steel)

The enamel-steel interface is important regarding bonding of the glass to the steel substrate. The interface should have a microscopically rough surface which is indicative of good bonding. A very smooth interface is usually seen when bonding is poor and in some instances flaking and/or fishscaling of the enamel may occur. Poor bond will also aggravate the tendency to chip on corners as well as when the article is twisted (torsion) to a minor degree. Figure 5 illustrates the enamel-steel interface.

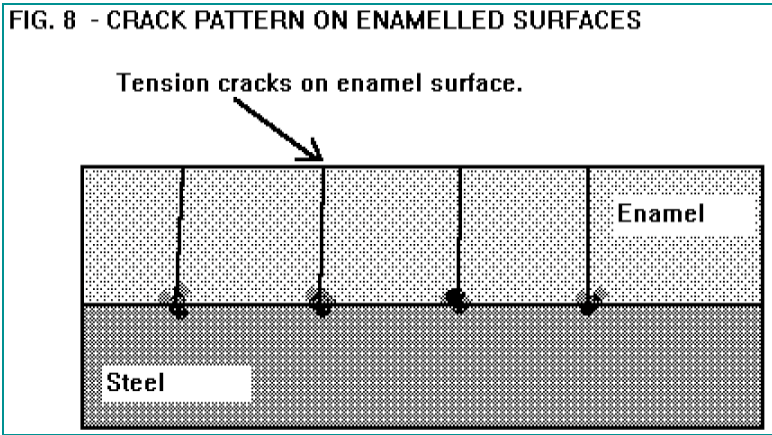
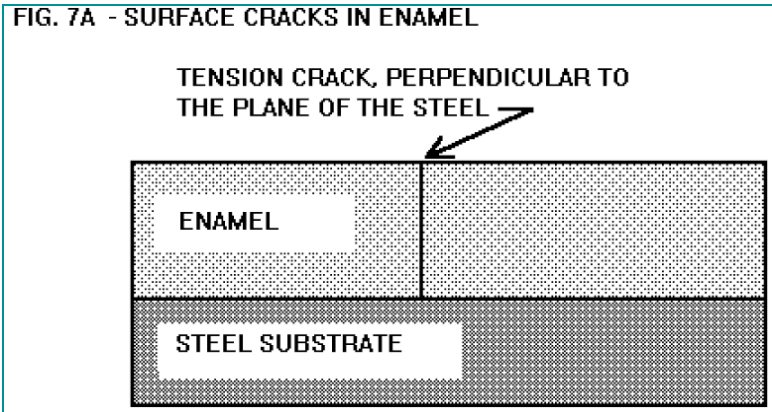
B. Corrosion Mechanisms

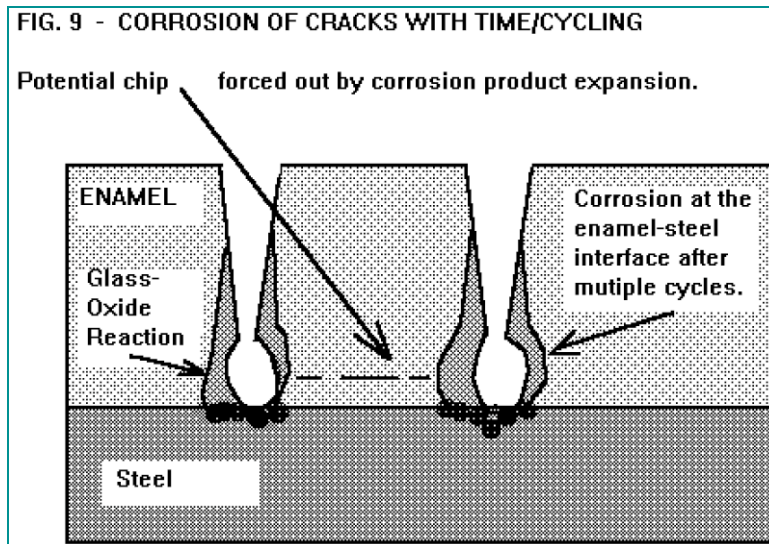
Corrosion which is detrimental to the appearance of the enamelled steel used for pyrolytic systems is stress-crack corrosion and discoloration. Stress-crack corrosion occurs due to the oxidation of the enamel-steel interface as the part is exposed for various lengths of time to high temperatures and oxygen. The corrosion rate of steel accelerates with increasing temperature and is very rapid at 1100 deg. F. (593 deg. C.), as shown in Figure 6. Since the cracking occurs on the first pyrolytic (and possibly broil) cycle, the subsequent appearance of the cracks with an increasing number of test cycles or time is mainly due to the progressive corrosion of the exposed steel via the crack crevices at the cleaning temperatures. Figures 7A to 9 illustrate the stress-crack corrosion mechanism. Deterioration of the enamel is also observed due to color change and surface appearance change. This is usually due to the high temperatures occurring near the heating source. Electric heating elements may achieve skin temperatures of 1650 deg. F. (899 deg. C.). A gas flame may reach temperatures of 1550 deg. F. (844 deg. C.). These temperatures are high enough to soften the nearby enamel and increase the rate of reactivity of the enamel and the steel. Enamel surfaces near the heating sources reach temperatures of 1100 to 1200 deg. F. (593 to 649 deg. C.).





The enamel normally “corrodes” the steel in order to dissolve a thin layer and produce an irregular interface that will allow the glass to flow into the minute crevices and adhere mechanically. At these surface temperatures, the steel and enamel will gradually react and the reaction products will diffuse into the enamel layer starting at the interface. The type of metal oxides in the glass will also affect the degree of color change that may occur on extended heating.





C. Thermal Expansion Factors

The thermal expansion characteristics of porcelain enamel have an important influence on the enamel-steel composite. High expansions will minimize the compressive stresses in the coating as low expansions will maximize the compressive stresses in a coating. Since pyrolytic systems must endure high temperature excursions as well as some uneven heating, the pyrolytic enamel systems are generally low expansion.

Some control can be exercised over the rate of expansion as well as the glass transition temperature. Small changes in these factors will have a large influence on the pyrolytic use properties.

Utilizing Enamels Effectively

Sheet enamels have a general firing temperature range between 1400 deg. F. and 1600 deg. F. (760 and 870 deg. C.). Higher processing temperatures will start to have detrimental effects upon steel strength, i.e., sag and distortion. Firing temperatures above 1550 deg. F. (843 deg. C.) are typical for pyrolytic systems with a good group of properties such as cleanability, heat test durability, colour control, and bond. The enamelled steel is analogous to a bi-metallic strip. The differences in expansion of the components will make the composite bend in predictable directions. In addition, the constraints on movement are also of importance. The wall section of an oven, either the top (over the broil section for electrically heated ovens) or the bottom (either under or over the heat source) are "constrained beams" as shown in Figure 10. The curved corners of an oven act as constraints to hold the assembly rigid. Between the sides the center section will flex in response to a stress or load. In the case of ovens, the heating source provides the stress via the expansion response due to temperature elevation. As the metal and glass composite expand, they will move in an effort to relieve stress and move in a predictable direction. Coating both sides of sections of parts to control the movement of the composite has been used successfully that reached temperatures up to 580 deg. F. (300 deg. C.). A simple "rule of thumb" is that the composite will bend towards the side with the thicker enamel coating. Figures 11 to 13 indicate the sides with more or less compression depending on the enamel thickness.

FIG. 10 - CONSTRAINED BEAM

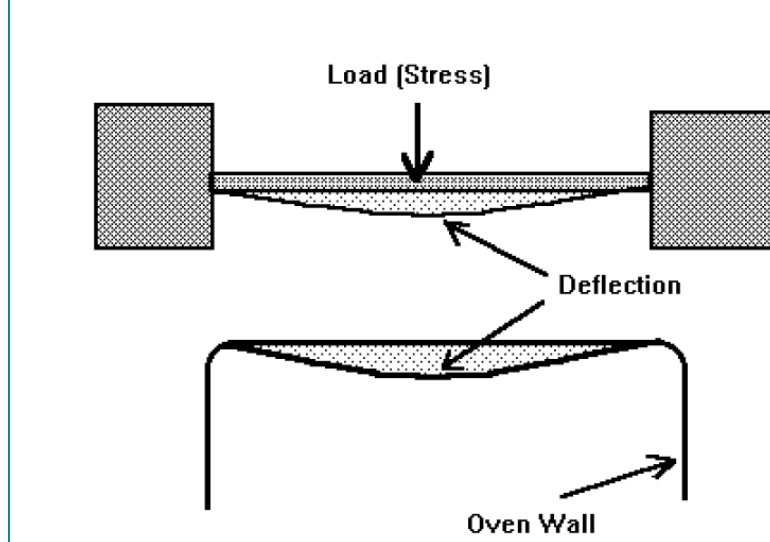
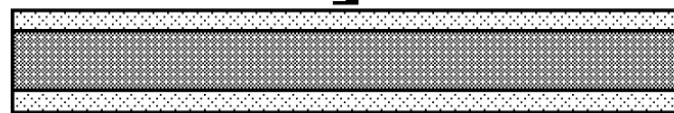


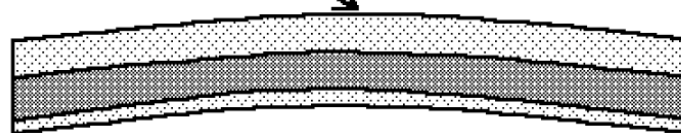
FIG. 11 - EFFECT OF COUNTER ENAMEL ON COMPOSITE WARP

Enamel on top and bottom side of steel.

a. Equal enamel thickness



b. Enamel thicker on top



c. Enamel thicker on bottom

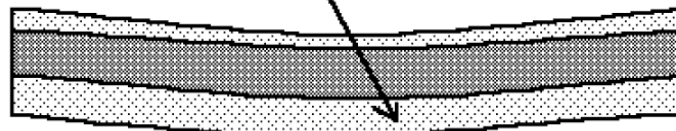


FIG. 12 - TENSION AND COMPRESSION IN ENAMEL LAYERS

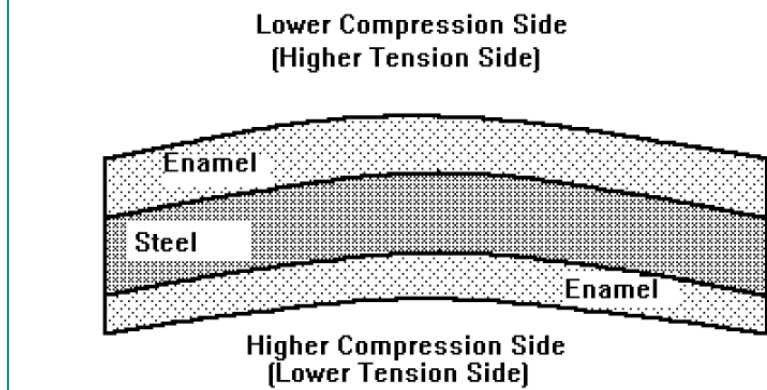
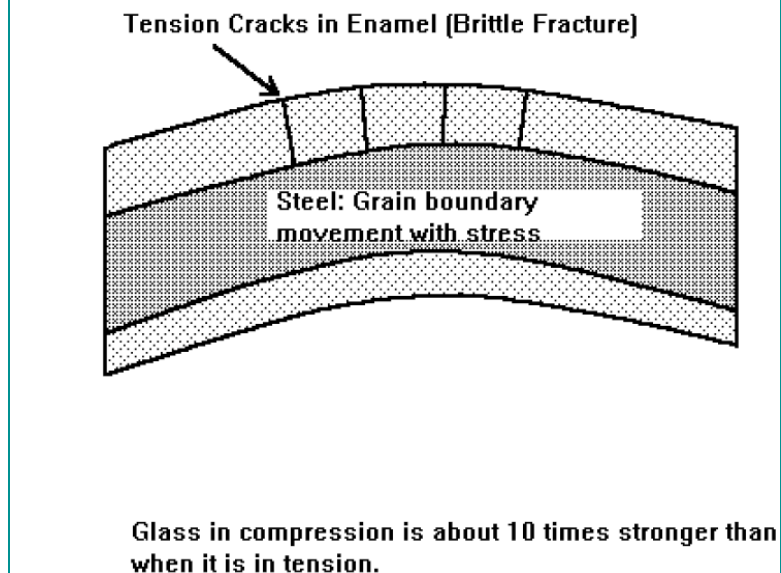


FIG. 13 - TENSION AND COMPRESSION IN ENAMEL LAYERS



Conclusions

1. Constraint of the enamel-steel composite will cause cracks to occur if the temperature causes the strength of the enamel to be exceeded. In practice, cracks occur about 850 deg. F. (454 deg. C.). Faster heating may lower this temperature.
2. The side on which stress cracks occur can be controlled on flat surfaces by applying a heavier coat of enamel on that side.

Additional Notes PEI -Porcelain Enamel Institute, Inc., Nashville, Tennessee USA AHAM - Association of Home Appliance Manufacturers, Chicago, USA (312) 984-5800

References

- 1 A. I. Andrews, *Porcelain Enamels*, 2nd ed., Garrard Press, Champaign, Ill., 1961, p. 76
- 2 G. W. Scherer, *Relaxation in Glass and Composites*, Krieger Publishing Co., 1992, Chap. 8.
- 3 R. L. Myers, *Appliance Engineer*, Vol. 6, No. 2, p. 23 (1972).