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Welding – A Non-Linear Conundrum

Welding is a one of the many processes used in manufacturing on the shop-floor; other processes include machining, stamping, molding, etc. Even though welding is commonly used, it is not well understood on how it works and the related importance of process control and process windows. One of the main reasons for this difficulty is due to the fact that welding, in comparison with other manufacturing processes, happens to be a non-linear process making it difficult to interpret. For example, when a cutting tool bit is advanced by 0.002" on a turning lathe, it will reduce the part radius by 0.002" forming a linear relation. However, a 20% decrease in weld energy will not result in 20% reduction in weld strength; often the drop in strength is much greater.

Welding is a unique process where a very small volume of material is expected to melt while the neighboring regions, even less than a millimeter, are expected to remain at room temperature. In order for this to be possible, the rate of temperature rise has to be much higher compared to the rate of heat loss. If the rate of heating is not high enough, then the heat input will be rapidly dissipated by conduction leading to a large area being heated but without any melting. To put this rate issue in perspective, most structural alloys have a melting point greater than 1000°C and can be heated to a molten state (laser, resistance, TIG, or electron beam) in a milli-second; that corresponds to a rate rise of a million degrees per second! Quite amazing when you think about it like that.

In order to understand the non-linearity of the process, we can start with laser welding as an example. In laser welding, a pulse of laser light is programmed to hit the part surface for a fixed amount of time. At the beginning of the pulse, the initial photons are hitting a cold (room temperature) surface where the absorption is quite low; one of the factors that affects absorption is temperature (see Figure 1). At low absorption levels, most of the photons are reflected and constitute energy loss. The few photons that are absorbed get converted to heat which raises the local temperature. As the surface temperature increases, the absorption rate increases, and the next wave of photons that impinges on the surface are absorbed at a greater fraction. The higher fraction of photon absorption leads to more rapid increase in temperature, which leads to a further increase in absorption, thus forming a chain reaction that causes a rapid rise in temperature to melting point. This chain reaction is what makes it possible to melt a spot in a fraction of second, and what makes the process non-linear. The chain reaction rate is affected by power density in the laser spot, because it has to be high enough to cause that chain reaction to be initiated. If the power density is below that threshold, it is possible that you may never get any melting as the heat loss is far greater than the absorption rate. For example, let's say you are spot welding aluminum at 6 kW peak power pulse to produce a weld spot that is 0.020" (0.5 mm) in diameter and depth. But then you decide to reduce the power by 50% to 3 kW, you will find that the weld spot is much smaller than half and quite possibly the pulse many not produce any spot at all! Producing the desired spot size is a fine balance between power density and material properties, and even a small shift in conditions such as a dirty lens cover that cuts off 20% of the power may result in a 50% drop in weld spot size and penetration. This non-linearity is what makes welding an interesting and challenging process to control.

And it is not just laser welding; the non-linearity is true for all welding processes, and more so for processes where welding occurs in a short time including resistance welding, spot TIG welding, e-beam welding. The non-linearity in resistance welding comes from changes to material resistivity with temperature; as temperature rises, so does its resistance. Assuming you are welding stainless steel, the initial bunch of electrons flowing through the parts produce only minor heating effect as the bulk resistance is quite low. As the parts get warm, the resistance increases, and sets up a chain reaction that quickly results in melting to form a nugget. Like photon absorption in laser welding, the increase in resistance with temperature makes it possible to have such a rapid heating. Figure 2 shows relation between energy (current) and strength for a resistance weld. The curve is based in real data but I have not displayed the units since the trend is the important part of the discussion and will be similar no matter the size of the weld. Trend shows a non-linear relation of strength with respect to input current with most of the strength being generated by the final 20% of the increase in energy. If this process was linear, the trend would have followed the dashed line shown. Increase in strength is usually capped by some physical limitation such as maximum strength of base material, unacceptable flash, or excessive sticking.

One of the biggest challenges with this non-linearity is the difficulty in managing the weld strength by tweaking the weld energy, without fundamentally changing the part design, process, or materials. If you try to reduce the weld strength by reducing weld energy, you may find yourself on the slippery slope where the weld strength will not be robust (lots of variation, low Cpk) and failure modes also may not be predictable. A welding engineer will do well to steer clear of such slopes and try to get the process up over the plateau.

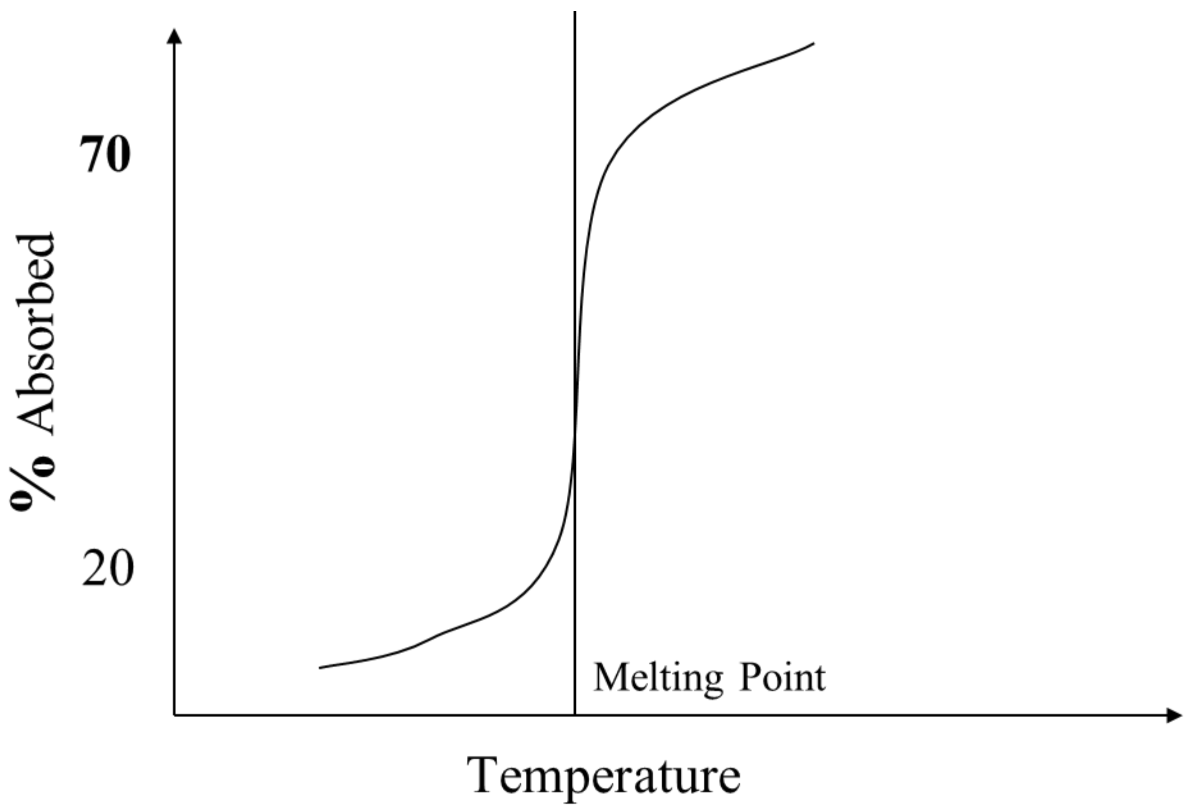

Figure 1. Schematic shows absorption as a function of temperature; absorption increases dramatically as temperature reaches and crosses the melting point.

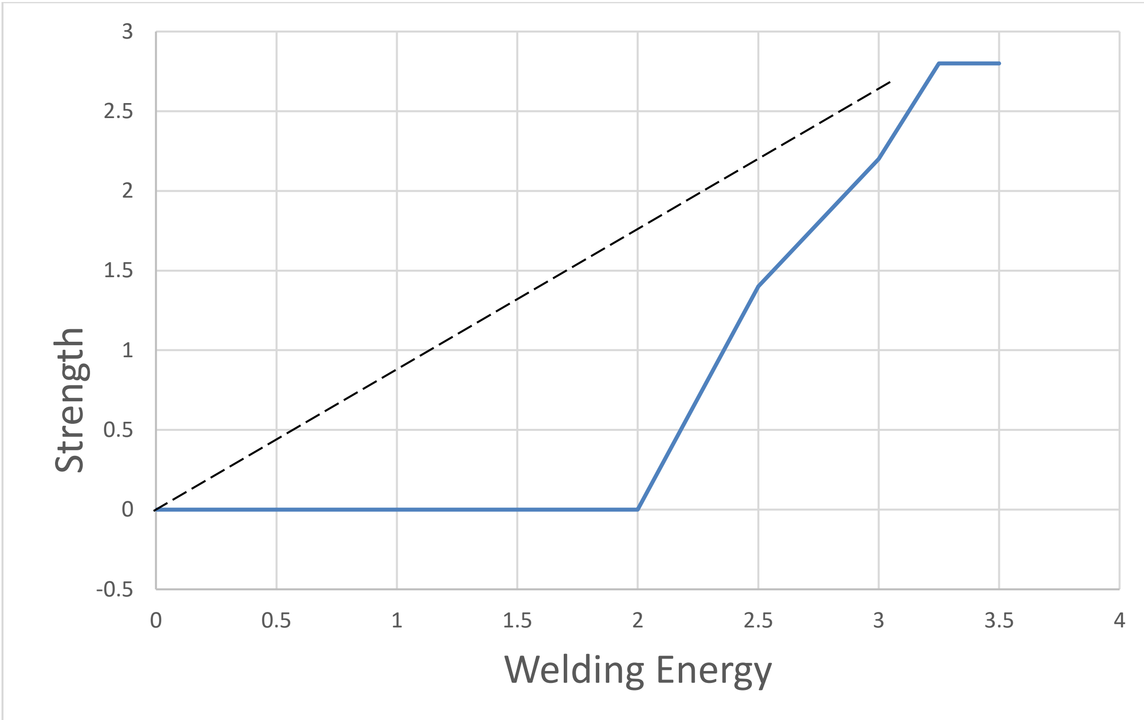

Figure 2. Graph shows effect of welding current on welds strength for typical spot welding application. Notice the lack of weld strength with initial input of weld energy followed by a steep rise towards the end. The dashed lines shows a hypothetical linear relation.