Weld setup, variable frequency and heat affected zones in high-frequency tube and pipe welding

By Bjørnar Grande, Olav Wærstad and Peter Runeborg (EFD Induction)

The article investigates the impact that geometrical changes in the weld zone have on weld frequency and the Heat Affected Zone (HAZ). The article evaluates the consequences of controlling HAZ by a variable frequency option. The article points out the importance of weld setup control.

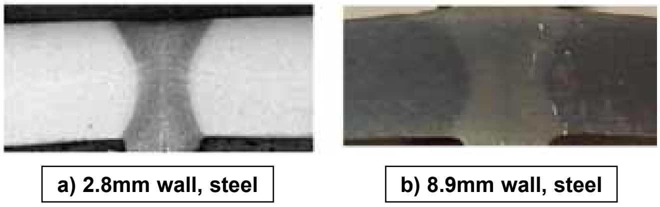

Figure 1: Real 2D heat affected zones

Introduction

Tube and pipe manufacturers aim to achieve and repeat successful production runs – something requiring knowledge of the impact of many parameters in the manufacturing process. One of the first theoretical research works based on Finite Element Method calculations on the two-dimensional (2D) heat affected zone (HAZ) was published in 1998, with the focus on weld frequency [1]. Further studies focused on geometrical variables of the weld vee [2, 3]. A key result of this research was the realisation that geometrical parameters have a significant impact on the HAZ. This suggests that more attention should be paid to weld setup control in order to obtain the desired HAZ.

In addition to the use of welder recipes (tube identification, power set point, energy monitoring factor, etc) weld setup recipes should be used to maintain the HAZ for all production batches of a product [9]. Other published research focused solely on the weld frequency's impact on the HAZ, and has resulted in a proposed welder concept that includes frequency adjustment to control the HAZ [6, 8]. This paper, from a principal point of view and based on a 2D model of the HAZ, investigates the proposed concept's ability to repeat a product's HAZ throughout production.

Heat affected zone

The heat affected zone is typically defined as the area of base metal where the microstructure and material properties have been altered by the welding process and subsequent re-cooling. One author defines the HAZ as any metal heated to 650°C (1,200°F) or hotter [4]. Figure 1 shows two weld samples, wall thicknesses of 2.8mm (0.11") and 8.9mm (0.35"), for two common steel materials. The hourglass shape of the HAZ is clearly visible, showing that the heating of the faying strip edges is not uniform across the wall thickness.

HAZ control concept

One main objective of the proposed HAZ control solution is to reproduce the HAZ of an earlier production run [5, 6]. The proposal makes two separate but related claims:

1) It is possible to calculate the 1D temperature distribution in the x-direction, and the maximum vee wall surface temperature at x=0, provided we know certain tube material properties, the weld speed and the weld vee length (Figures 2a and 2b)
2) Weld frequency and welder output power can control the 1D temperature distribution in the x-direction, and the maximum vee wall surface temperature at x=0

With the ability to estimate the shape of this heat distribution, the HAZ width can be calculated and controlled. The HAZ width is given by the temperature assumed as the lower limit of the HAZ. It is denoted ½ * HAZ in Figure 2b, since the total HAZ is given by the area of heated material on both tube wall edges.

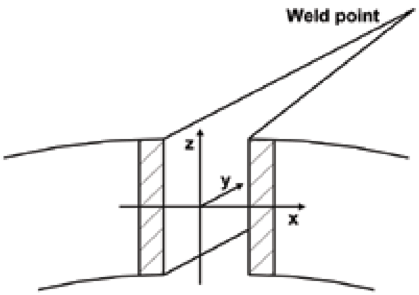

Figure 2a: System of axes

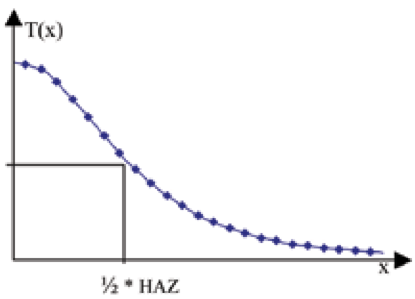

Figure 2b: Temperature distribution

If the calculated HAZ width is not as requested, the weld operator or a computer must adjust frequency according to the following:

- Calculated HAZ width < requested HAZ width ⇒ reduce frequency
- Calculated HAZ width > requested HAZ width ⇒ increase frequency

In addition, welder output power is adjusted by the operator or calculated by a computer program to give the required energy input to obtain the requested HAZ width and weld temperature at the vee wall surface (x=0).

The HAZ at the weld point is the most significant parameter, so T(x) is calculated at y = vee length. The whole concept is based on uniform current distribution in the weld vee walls and a uniform temperature across the weld; that is, a 1D model [8].

Parameters influencing the HAZ and investigation procedure

A number of parameters influence the weld temperature and heat distribution in the weld vee, thereby affecting weld quality. Loebbe presents 16 such parameters [7]. Focusing on the HAZ and the geometrical parameters that can change over time in the weld zone, we examine the following:

- Weld vee angle and springback
- Moving weld point, continuously changing position
- Non-stable vee angle ('breathing' vee), continuously changing vee angle
- Distance weld point – coil (or contacts); the vee length

One idea critical to the proposed HAZ control concept is to reproduce from an earlier production run the temperature distribution and the maximum weld temperature at the tube wall's surfaces. In the proposed concept, the two parameters to be adjusted (by the operator or computer system) are the welder frequency and welder power. The first step is, therefore, to determine how changes in the weld setup parameters alter the resonance circuit's frequency and the required load power. This is what we call the *process response*. The second step is to identify the adjustments of welder frequency and welder power, according to the proposed control concept. This can be called the *system response*.

The final step evaluates how this system response affects the HAZ, which has already been altered by the initial change in the weld set-up (compared with the previous production run). This lets us evaluate the overall value of the proposed system.

Process response

The resonance frequency for both series and parallel resonance circuits is given by:

$$f_0 \approx \frac{1}{2\pi\sqrt{(L_i + L_{Load})\cdot C}}$$

Note: Valid for both current-fed and voltage-fed inverter-based welders

C is the total capacitance of the electrical circuit and is given by the installed compensating capacitors inside the welder's cabinet. L_i is the internal inductance of the welder and consists of the inductance in coil leads, busbar and the output circuit parts inside the machine's cabinet. L_{Load} is the load inductance and, in the case of induction welding, can be divided in three parts:

- $L_{OD\ tube}$; mainly due to air gap between the induction coil and the outside surface of steel strip
- L_{Vee} ; mainly due to air gap between the strip edges in the weld vee
- $L_{ID\ tube}$; mainly due to impeder and air gap between impeder and inside surface

The two last inductances are in parallel in the equivalent electrical circuit (Figure 3). The process responses are listed in Table 1. It is important to note that these responses are independent of welder type. These are the process responses. The symbol '-' denotes no change.

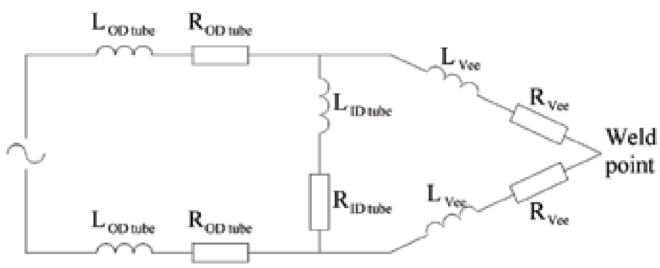

Figure 3: Electrical circuit model of tube (strip)

Table 1: Process responses to parameter changes

Parameter	Change	L_{vee}	L_{IDtube}	L_{ODtube}	L_{Load}	Frequency	Power
Vee angle	Wider	Inc(rease)	-	-	Inc	Dec	Inc
	Narrower	Dec(rease)	-	-	Dec	Inc	Dec
Springback	More	Inc	-	-	Inc	Dec	Inc
	Less	Dec	-	-	Dec	Inc	Dec
Moving weld point	Downstream	Inc	-	-	Inc	Dec	Inc
	Upstream	Dec	-	-	Dec	Inc	Dec
Vee length	Longer	Inc	-	-	Inc	Dec	Inc
	Shorter	Dec	-	-	Dec	Inc	Dec

System response

The investigation of the system response and its influence on the HAZ starts with a change in the weld vee angle. First, the proposed HAZ control concept [5, 6] is investigated, followed by an evaluation of a welder design (with constant internal inductance) without the feature of step-less adjustable frequency. In the proposed system, power input is one of two parameters to be adjusted. If power can not be adjusted within set tolerances of the reference run, the operator must check and adjust weld setup to get the same power as in the previous production run. This is exactly the same procedure as for a plain welder that does not include the proposed concept. All welders should have a feature such as a weld recipe for each product to be welded [9]. Power can then be compared against a recorded value for the reference product. Further investigation of frequency adjustment and HAZ control, therefore, will be based on required power being within set tolerances after a change in the actual parameter.

Weld vee angle

Figure 4 summarises the results of previous research [1, 2, 3]. A wider vee angle and higher frequency have both the same principal impact on the HAZ. In resonance frequency, the process response to a wider vee angle is a lower frequency (Table 1). The wider vee angle results in a more pronounced hourglass-shaped HAZ (Figure 4). To keep the calculated HAZ width unchanged, the proposed system's response to a wider vee angle is to increase the weld frequency to that of the reference production run. But, according to Figure 4, this response does not compensate for the initial change in HAZ, as would be expected for a control system. On the contrary, it amplifies the change by increasing the heating of the corners. The outcome of this situation, with the HAZ control concept, is that production continues to run, at a somewhat higher power (within accepted tolerances), with a more pronounced and amplified hourglass-shaped HAZ than for the reference run. A welder without the step-less variable frequency option also continues production with the changed HAZ shape, with the somewhat higher power output, but at the lower frequency (process response). The initial change in HAZ, due to the wider vee angle, is somewhat counteracted by the natural reduction in frequency (Figure 4). Figure 5 summarises these effects.

In case the initial parameter change is a narrower weld vee angle, the process response, the system's response and change in HAZ are all in the opposite directions. The final outcome is, however, the same as outlined above.

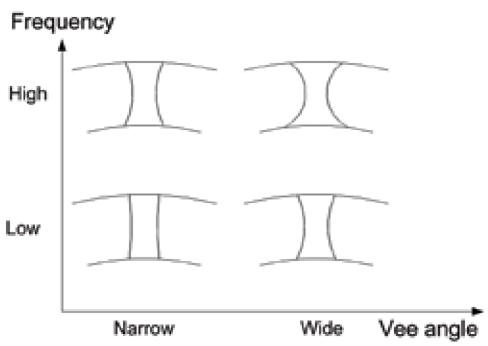

Figure 4: HAZ shape vs frequency and vee angle

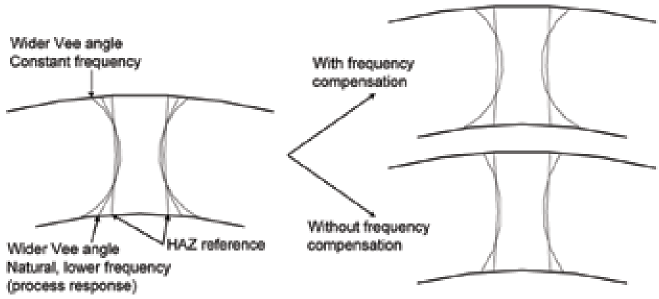

Figure 5: Implications of change to wider vee angle for the HAZ

Springback

The resilient flexing of the strip edges, also called springback, was investigated with respect to both heating of the corners of the strip and depth of heating in the centre of the tube wall [2]. The more pronounced the springback, the more pronounced the hourglass shape of the HAZ. The springback has the same influence on HAZ shape as the vee angle.

As can be seen in Table 1, the process response in the springback case equals that of the weld vee angle. The system response of the proposed HAZ control concept will then be identical to the one described above for the vee angle. The final result is that no real HAZ control has been achieved by the proposed HAZ control concept, which amplifies the initial change in the temperature distribution.

Moving weld point and breathing vee

Situations with a moving weld point and the 'breathing vee' are most likely to occur at the same time. As the weld point moves downstream and upstream, the distance between the strip edges increases and decreases accordingly. This is a situation with a continuously changing effective weld vee angle and length. Analysis of the results shows that the heat penetrates deeper into the material in circumferential direction both in the centre of the tube wall and at the outside and inside surfaces as the vee length increases [2]. The shape of the HAZ is relatively unchanged as the vee length (heating time) changes. But the overheating of the corners occurs as the heating time gets longer [3].

First, we assume that the weld point moves downstream. According to Table 1, the process response to an increased vee length is a lower frequency. Due to the request to keep calculated temperature distribution equal to the distribution of the reference run, the proposed system's response is to increase frequency. The initial, extra heating of the corners is strengthened by the increase in frequency. Next, when the weld point moves upstream, the opposite will happen. This means that the proposed system continuously amplifies the mechanically initialised HAZ changes.

Weld vee length

The distance from the weld point to the coil is an input value to the HAZ control system. Therefore, the evaluation in this paragraph is based on an incorrect input to the system. The purpose is to see how the system responds to this flawed input. First, we assume that the vee length is longer than the input value entered into the system. The process response to a longer vee length is a lower frequency. The system is not aware of the wrong input, and the HAZ control concept responds by adjusting frequency up, in order to calculate a HAZ width equal to the one in the reference run. The initial increase in heating of the corners is again reinforced by the increase in frequency. The opposite amplification will take place in case of a vee length shorter than the entered input value to the system.

Considerations and limitations

The calculation model used in the HAZ control concept presented by Scott and others has two shortcomings [5, 6]:

1. The high frequency current in weld vee is assumed uniformly distributed in the strip wall [8]
2. The proximity effect in the weld vee is not taken into account in the model

The first limitation results in a current and temperature distribution in the x-z-plane as shown in Figure 6. This is a 1D model of the HAZ. However, the HAZ is two-dimensional (2D) in the x-z-plane for a large range of wall thicknesses. This is shown in Figure 1, where the hour-glass shape of the HAZ is evident. This implies that the equations used in the 1D calculation model do not accurately describe what happens, electrically and thermally, at the inside and outside corners of the strip edges in the weld vee.

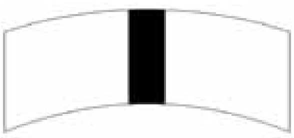

Figure 6: 1D model of HAZ

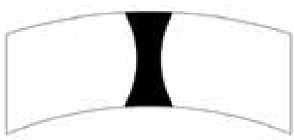

Figure 7: 2D model of HAZ

When the proximity effect – a fundamental effect in high frequency current welding – is not a part of the weld vee model, it means that changes in weld vee angle, springback and other geometrical parameters in the weld vee are not properly handled by the proposed concept. A real 2D model (Figure 7) takes into account the proximity effect and can describe the effects that take place at the strip corners and in the tube wall centre when high-frequency current is present. Although pointing out the weld vee angle as one of the parameters affecting the HAZ width [5, 6], the proximity effect's influence on the 2D temperature distribution in the x-z-plane of the HAZ is neglected in the proposed system.

It can be argued that a 1D model is valid for thin-walled products, where the 2D hour-glass shape of the HAZ is less pronounced. The wall thickness at which a 1D model can replace the real 2D model depends on strip material and weld vee angle. Figure 1a shows the 2D model's validity for a wall thickness of 2.8mm (0.11"). The hour-glass shape is pronounced in this picture, indicating that the 2D model must be valid for even thinner products. A theoretical study based on Finite Element Analysis shows that the HAZ is still two-dimensional at a wall thickness equal to 1.27mm (0.05") for low-carbon steel [4].

Summary

The above evaluation focuses on the impact of geometrical parameters on the HAZ, and the influence frequency adjustment has in maintaining the HAZ when the weld vee geometry changes. Other parameters, such as coil and impeder, are not covered. The general result of this investigation is that the inherent response of the HAZ control system is to amplify the initial HAZ change caused by geometrical alterations, rather than opposing changes, which would be an expected and desired response of a control system.

This 2D-model-based investigation shows that the ability to adjust frequency as described in the proposed concept can not compensate for changes in HAZ shape caused by geometrical changes in the weld zone. For the investigated parameter changes, the inherent property of the system is to ensure a constant frequency, regardless of the reason for the initial HAZ change. It acts more like a frequency control, rather than a HAZ control.

It is difficult to see that a variable frequency welder, with the proposed HAZ control system, gives the tube and pipe manufacturer any real added value in maintaining the HAZ and weld quality for every production batch of a product. In other words: real and true HAZ control requires weld setup control.

In a welder with a constant internal inductance (no step-less frequency adjustment), there is no extra adjustable inductance present that can reduce or mask a change in frequency due to a deviating weld process parameter. A repeated and unchanged weld frequency (and power) is then the direct result of a successful reproduction of the reference production weld setup, heat affected zone and weld quality.

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EFD Induction as – Norway
Email: sales@no.efdgroup.net
Website: www.efd-induction.com