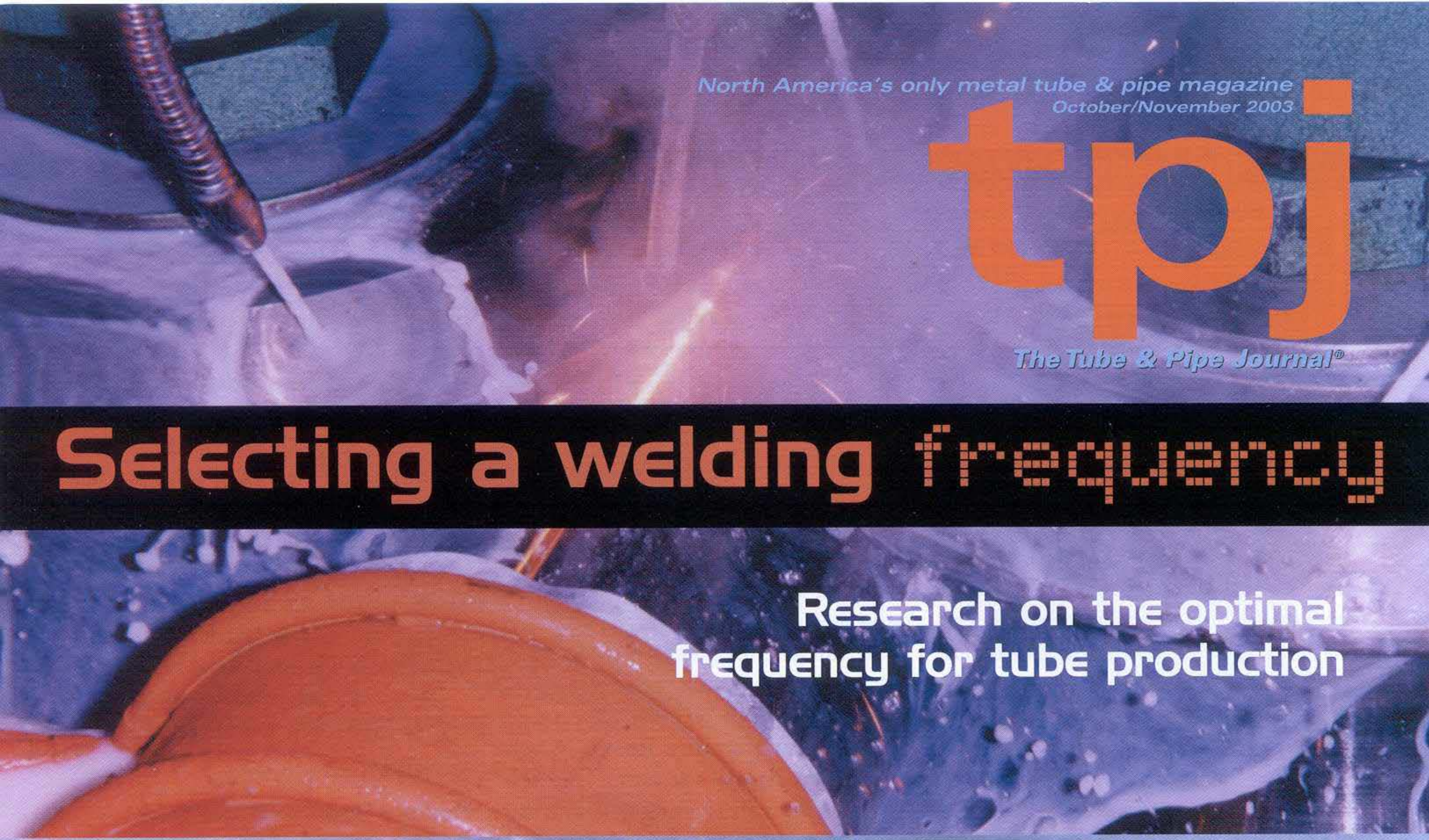

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Selecting a welding frequency

Research on the optimal frequency for tube production

By Paul Scott, Ph.D.

High-frequency contact and induction welding processes have been used in welded tube production for more than 50 years with little attention paid to the welding frequency. Traditional vacuum-tube-type welders operated at frequencies between 300 and 400 kilohertz (kHz). First-generation solid-state welders, which were introduced in the early 1990s, generally had frequencies that were much lower, the average being around 200 kHz. The lower frequency range resulted from early circuit designs used by some manufacturers and component limitations of the time.

This difference in welding frequency incited an ongoing debate: Some people in the industry felt that higher frequencies provided higher-quality tube and pipe, whereas others insisted that lower frequencies were an improvement over higher frequencies.

This debate resulted from a limitation of the welding equipment of the time. Only one frequency was available on any specific welding power supply. Recent advancements now allow tube mill operators to choose any frequency from a range of frequencies available on a single piece of equipment.

Choosing the most appropriate welding frequency for the particular material and thickness being welded can reduce welding defects, optimize the internal bead height, and reduce weld splatter. Using the optimum frequency for an application is especially critical when welding coated materials or when welding a variety of materials on one mill.

Finite element analysis (FEA) can help determine how welding frequency affects various characteristics of the finished weld. The latest software, designed for today's fast personal computers, has enabled analysis that formerly was practical only on supercomputers. Tools are readily available that enable both 2-D and 3-D studies that incorporate electromagnetic and thermal phenomena.

Metallurgical Interpretation of Temperature Data

FEA can be used to determine the temperature distribution in the weld just before the tube encounters the weld box squeeze rolls. For this article, the material selected is low-carbon steel. Interpreting the temperature data in terms of weld quality requires definitions of the temperatures at which various physical effects occur. While these temperatures vary depending on which alloy is used, the temperature values are similar, and the specific temperatures chosen should not affect the conclusions drawn from the results.

Three areas of concern with regard to temperature and its effects are the strip edge temperature, forge temperature, and heat-affected zone (HAZ) temperature. The temperatures for each of these are based on previous research or commonly available reference material.

Temperature Range	Interpretation
650 degrees C (1,200 degrees F) and higher	HAZ
875 to 1,450 degrees C (1,607 to 2,642 degrees F)	Forge temperature range
1,550 to 1,725 degrees C (2,822 to 3,137 degrees F)	Metal is partially molten
1,725 degrees C (3,137 degrees F) and higher	Metal is totally molten

Figure 1.

The temperature ranges and interpretations shown here correspond to typical low-carbon steel.

Strip Edge Temperature. The strip edge generally does not melt when using a good weld setup on thin-walled tube. However, melting usually occurs in the corners of the strip when welding thick-walled tube. It is assumed that the metal is completely melted if its temperature exceeds 1,725 degrees Celsius (3,137 degrees Fahrenheit) and partly molten if its temperature is between 1,550 and 1,725 degrees C (2,822 and 3,137 degrees F).

Because the FEA program does not include heat of fusion in its thermal model, the temperatures predicted in the molten region will be higher than those achieved in actual tube welding. However, molten is molten, and melting needs to be minimized to achieve a good forge weld without any cast structure. Molten material gets deposited on the impeder, which reduces its life. Also, buildup between the impeder and the tube can cause mill downtime.

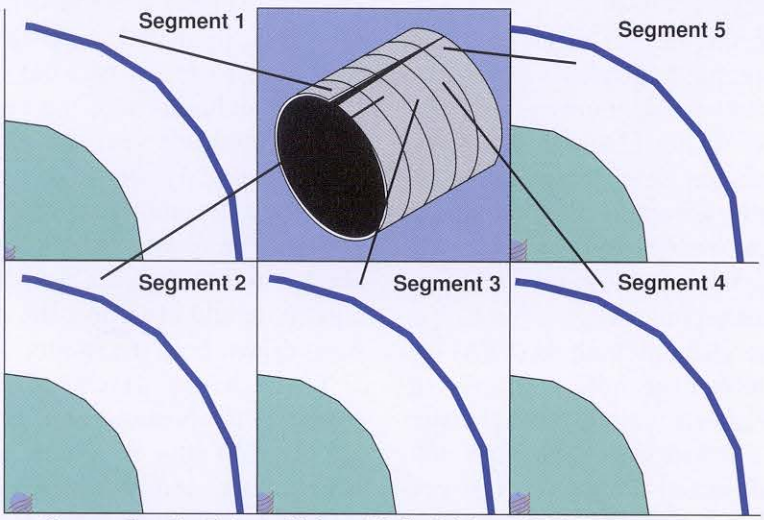
Regardless of the actual melting temperature, heating the material until it melts is to be avoided.

Forge Temperature Range. When the temperature of the metal is in the forge temperature range, it can be pressed together to create a forged weld. The forge temperature range is accepted to be from 875 to 1,450 degrees C (1,607 to 2,642 degrees F).

Related to the forge temperature and successful forge welding is the material's yield stress. At low temperatures the yield stress for low-carbon steel can be 340 megaPascals (50,000 pounds per square inch [PSI]). At about 540 degrees C (1,000 degrees F), the yield stress drops to approximately half of its room-temperature value. When heated to the forge temperature range, the steel's strength is 5 to 10 percent of its room-temperature value.

HAZ Temperature. The HAZ is defined as any metal heated to 650 degrees C (1,200 degrees F) or hotter. One of the goals of tube production is to minimize the width of the HAZ, because the local properties of the material will be different from those of the parent material. The HAZ generally is harder and more brittle than the unaffected material.

The strip edge, forge, and HAZ temperatures are summarized in **Figure 1**.



Segmenting the Tube to Make a 3D Model from Multiple 2D Models

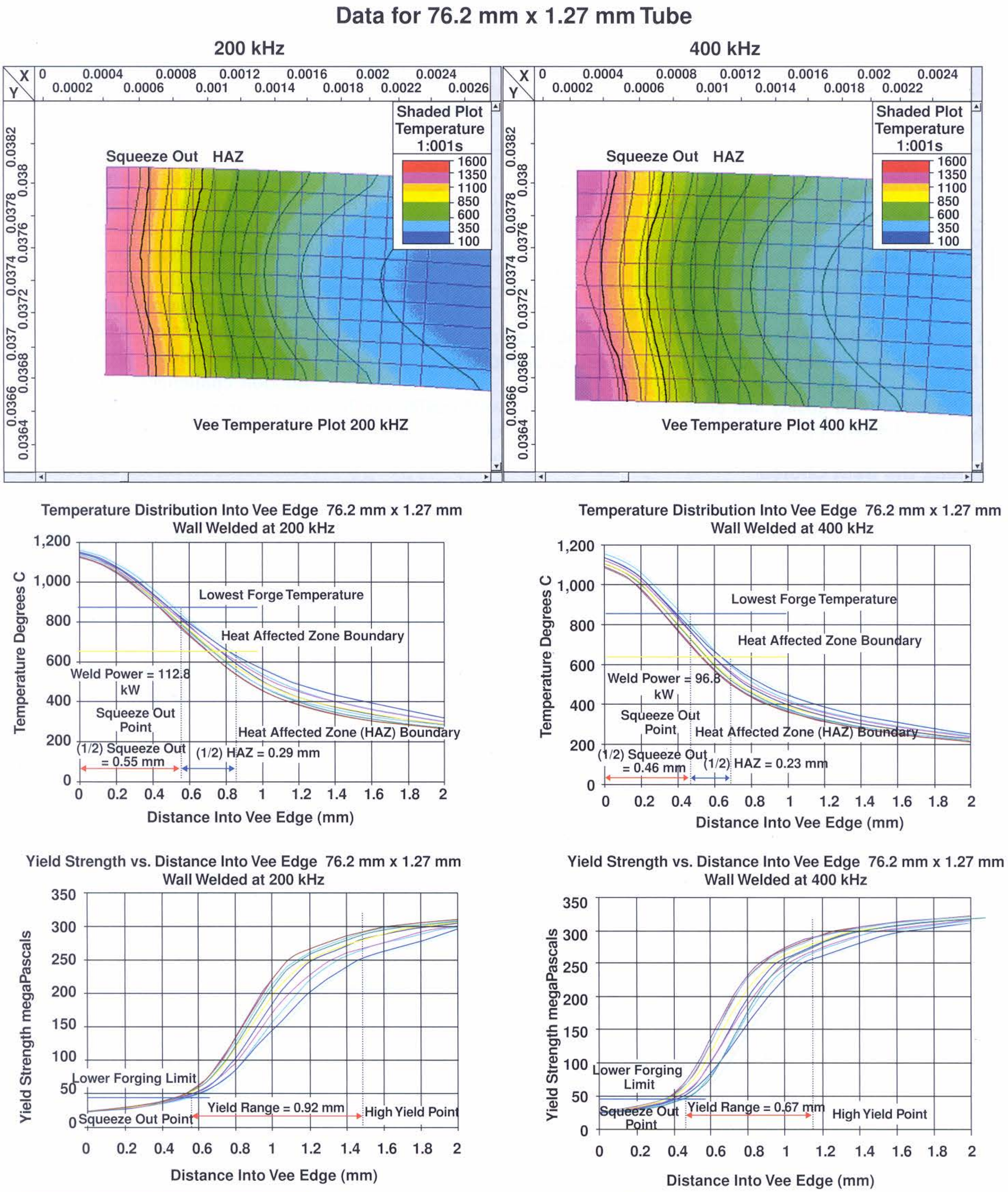
Figure 2.

The successive segments, or models, show the V space becoming continuously smaller. Several 2D models are used to emulate a 3D model.

Factors Used to Determine Weld Quality

Comparing the results of the FEA at various welding frequencies involves the following criteria:

- **Weld power.** Weld power can be calculated directly from the temperature field by determining the amount of energy necessary to raise each element to its final temperature. One goal of efficient tube production is minimizing weld power.
- **Amount of squeeze-out.** Squeezing out the right amount of material during the forging process is critical to achieving a good weld. The amount of material squeezed out is calculated by determining the circumferential distance from the strip edge to the lower boundary of the forge temperature range (875 degrees C) and multiplying this distance by two.
- **HAZ width.** Minimizing the HAZ width minimizes the amount of material that has properties that are different from those of the parent material. The HAZ width is found by establishing the circumferential distance from the end of the squeeze-



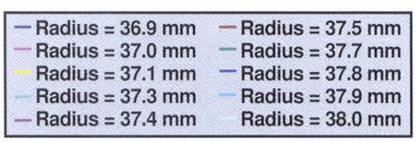


Figure 3.

Although both frequencies produced satisfactory welds, all criteria indicate that 400 kHz produced a higher-quality weld. The weld at 200 kHz used more weld power, resulted in more total squeeze-out, wider HAZ, and wider forge stiffness zone. The higher amount of squeeze-out also means that more material was consumed.

Data from Model of 76.2 mm x 1.27 mm Tube			
Criterion	200 kHz	400 kHz	Difference
Weld Power	112.8 kW	96.8 kW	16.5%
Total Squeeze Out	1.1 mm	0.92 mm	19.6%
Total HAZ Width	0.58 mm	0.46 mm	26.1%
Forge Stiffness Width	0.92 mm	0.67 mm	36.3%

Figure 4.
A summary of data from the thin-walled example indicates the 400-kHz frequency is superior to the 200-kHz frequency in every measured parameter.

out point to the point of the minimum HAZ temperature (650 degrees C), and multiplying this distance by two.

• **Quantity of molten material.** The amount of molten material, which is to be minimized, is the cross-sectional area of the V that is hotter than the partially molten temperature, or 1,550 degrees C (2,822 degrees F).

• **Forge stiffness.** A good forge weld is achieved by applying sufficient pressure when the material is in the correct temperature range. The amount of pressure that can be applied depends on the yield characteristics of the material, which are affected by temperature.

The yield profile in the V region is determined by converting the temperature of each element to yield strength. The distance between the squeeze-out point and the point at which the yield strength is 250 mPa is used to quantify V stiffness. A larger distance equates to less stiffness and therefore lower forge pressure for equivalent strip width.

Considerations in Finite Element Modeling

A reasonably detailed FEA model can help illustrate how the inducted or injected current flows in the V area and causes the V to heat to a temperature in the forge welding temperature range. While many methods can be used for constructing this model, the method used here employs successive 2-D models because it seems to provide the optimal compromise with regard to accuracy, computational run times, computer memory capacity, and disk storage requirements.

This approach divides the V into several segments and constructs a 2-D model of each segment (see **Figure 2**). The program first analyzes the V segment just after the induction coil or contacts first, and uses the final temperature distribution of this model as the initial temperature distribution for the next model. This process continues until it completes the last model, which analyzes the V edges just before they enter the squeeze rolls.

Modeling Results

Two tubes, one thin-walled and one thick-walled, were evaluated with FEA at both 200 and 400 kHz.

Thin-walled Tube. The thin-walled tube's specifications are 76.2 millimeter (3 inches) diameter and 1.27 mm (0.050 in.) in wall thickness. The tube was produced at 91.4 meters per minute (300 feet per min.) using a 76.6-mm (3-in.) V length and a 5-degree V angle. Experience with this tube indicates that 1 mm of total squeeze-out is the most desirable amount.

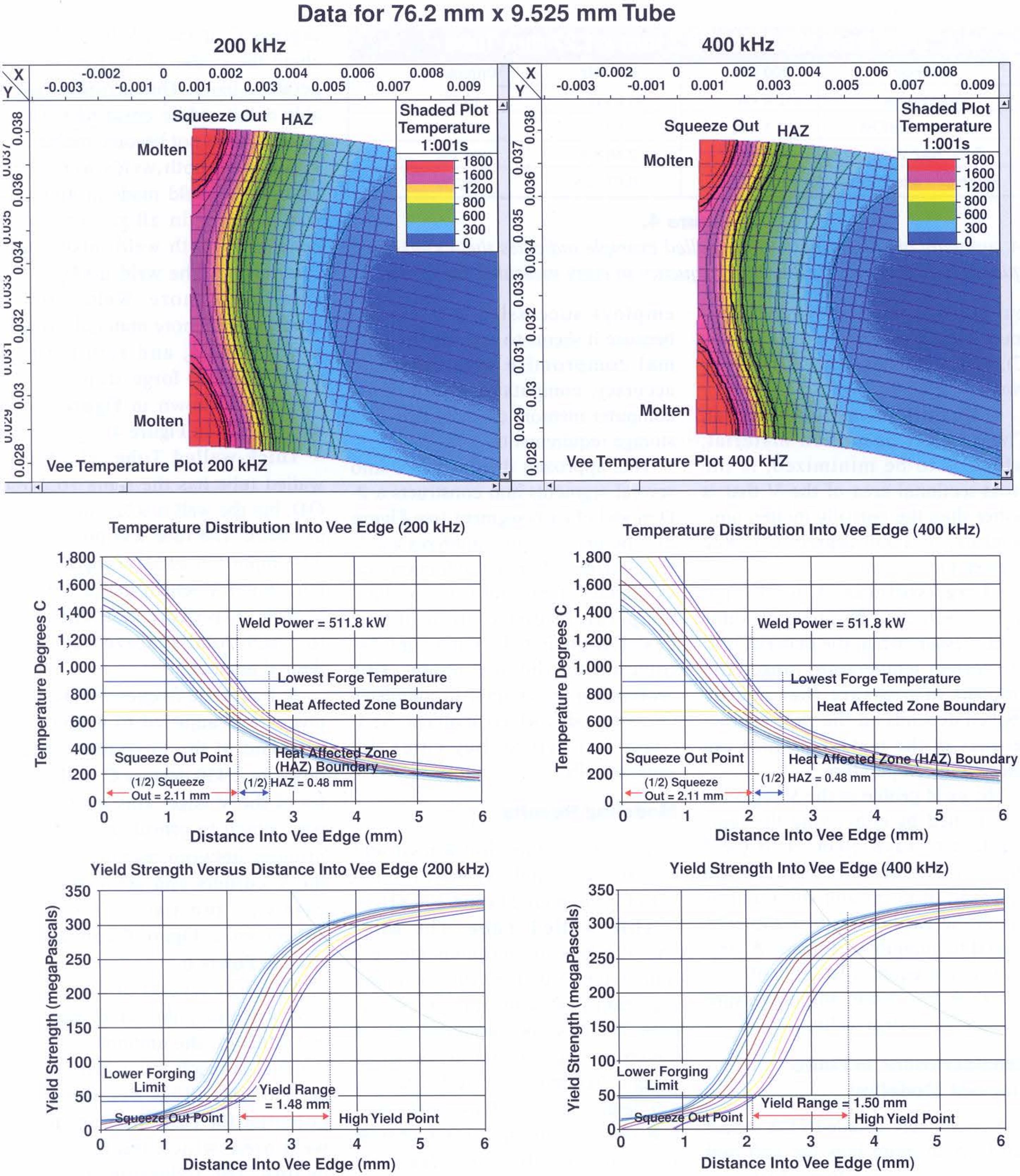
At both weld frequencies, 200 and 400 kHz, the weld power was adjusted to achieve an initial forging temperature of approximately 1,175 degrees C at the V edge, which is about the center of the forging temperature band. This provides favorable results while ensuring that the material does not become molten.

Although both welds were satisfactory, the weld made at 400 kHz was superior in all respects with benefits in both weld quality and cost savings. The weld made at 200 kHz used more weld power, squeezed out more material, created a wider HAZ, and resulted in a wider band of forge stiffness. The results are shown in **Figure 3** and summarized in **Figure 4**.

Thick-walled Tube. The thick-walled tube has the same 76.2-mm OD, but the wall is 9.525 mm (0.375 in.) thick. The tube was produced at 22.9 mpm (75 FPM) using a 152.4-mm (6-in.) V length and a 5-degree V angle. Experience indicated that 4 to 5 mm total squeeze-out is the desired amount.

At both weld frequencies the weld power was adjusted to achieve the high end of the forge temperature range, or 1,450 degrees C, at the center of the V edge. This temperature was chosen to provide a good compromise between melting metal in the V corners and achieving sufficient weld penetration. The results are shown in **Figure 5** and summarized in **Figure 6**.

Although several of the criteria were essentially the same regardless of frequency, the amount of molten material is much less when welding at 200 kHz. This decreases the potential for cast structure in the weld area, which improves weld quality. The reduction in molten material tends to make the V apex point more stable. The impeder will last longer and less metal will drip inside the tube. Therefore, the lower frequency provides the opportunity



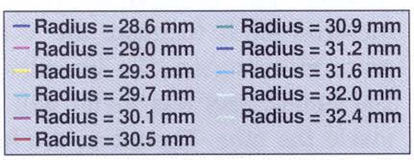


Figure 5.

For thick-walled tube, many of the criteria–weld power, total amount of squeeze-out, HAZ width, and forge stiffness width–are essentially the same regardless of weld frequency. However, when 200 kHz is used, approximately 20 percent less metal is melted in the V corners than when 400 kHz is used.

Data from Model of 76.2 mm x 9.525 mm Tube			
Criterion	200 kHz	400 kHz	Difference
Weld Power	511.8 kW	500.1 kW	2.3%
Total Squeeze Out	4.22 mm	4.18 mm	1.0%
Total HAZ Width	0.96 mm	0.96 mm	0%
Forge Stiffness Width	1.48 mm	1.50 mm	-1.3%
Molten Area Outside Tube	1.37 mm^2	1.67 mm^2	-18.0%
Molten Area Inside Tube	2.46 mm^2	3.14 mm^2	-21.7%

Figure 6.

A summary of data from the thick-walled example indicates welding at 200 kHz produces a somewhat better weld than welding at 400 kHz.

for improved weld quality and possibly less mill downtime.

Making the Best Choice

High-frequency welding is a very forgiving process when used on low-carbon steel; good welds can be achieved over a range of frequencies. However, better weld quality can be achieved by carefully researching the results achieved with different weld frequencies. In general, welding thinner-walled tubes at higher frequencies and thicker-walled tubes at lower frequencies improves tube qualities. Exceptions might be coated materials or special alloys that require experimentation to determine the welding frequency that yields the best overall weld quality. FEA is a practical tool for finding the optimal welding frequency, regardless of the wall thickness or material.

The combination of FEA and the ability to vary the welding unit's frequency can help a tube producer enhance its current tube production and accommodate any future production challenges associated with ever-changing markets.

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