Chapter 28

Finite Element Simulation of Magnetic Pulse Welding

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Finite element (FE) simulation of high strain rate deformation in MPW is of paramount significance to examine and predict the characteristic of impact welding before initiating laboratory experiments which is a very costly affair. At the same time FE simulation of MPW is very challenging task because of the coupled physics and dynamics nature of impact welding process. In the present study axis symmetry model (Figure 28.1) is used for FE simulation consisting of two parts clad (T91 Flier Tube) and end plug (T91 Rod) to envisage the effectiveness of impact welding for given input parameters. Section view of MPW setup is shown in Figure 28.1.

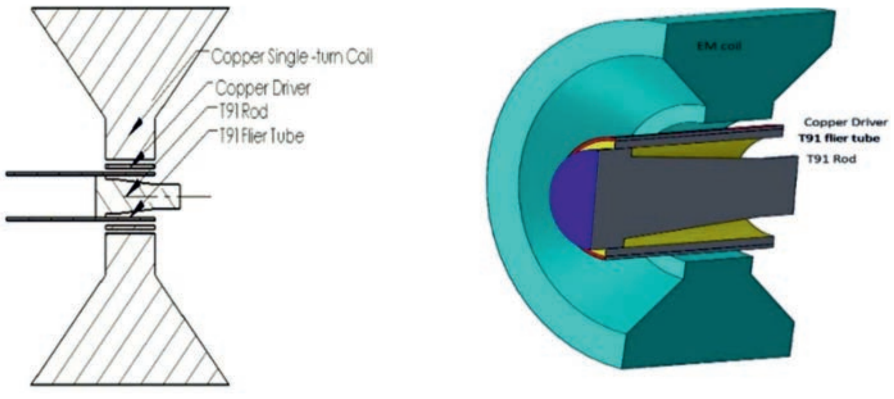

Figure 28.1. MPW set-up for T91 fuel pin.

Input current Frequency of 34.5 kHz and amplitude of 850 kA are considered as input parameter in the analysis. Impact angle between T91 clad and end plug is 5° (Figure 28.2).

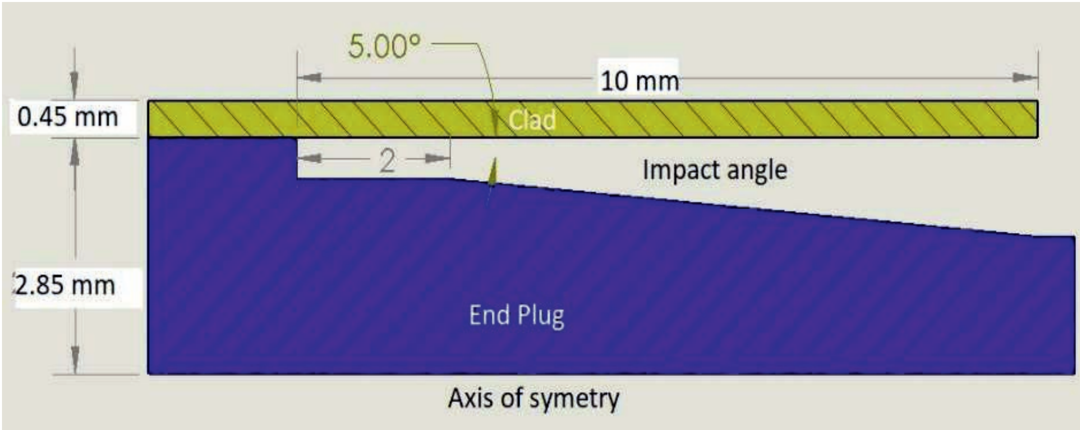

Figure 28.2. Geometrical detail and boundary condition of FEA model.

28.1. Magnetic Pressure/Loading

Pressure developed on the clad as result of impulse magnetic flux is shown in the Figure 28.3 which is a function of time and space. Magnetic field and magnetic pressure developed in coil calculated analytically. Peak pressure acting on the clad is 904 MPa.

$$B(magnetic\ field) = K \times \frac{\mu \times n \times I(t)}{l}, \tag{28.1}$$

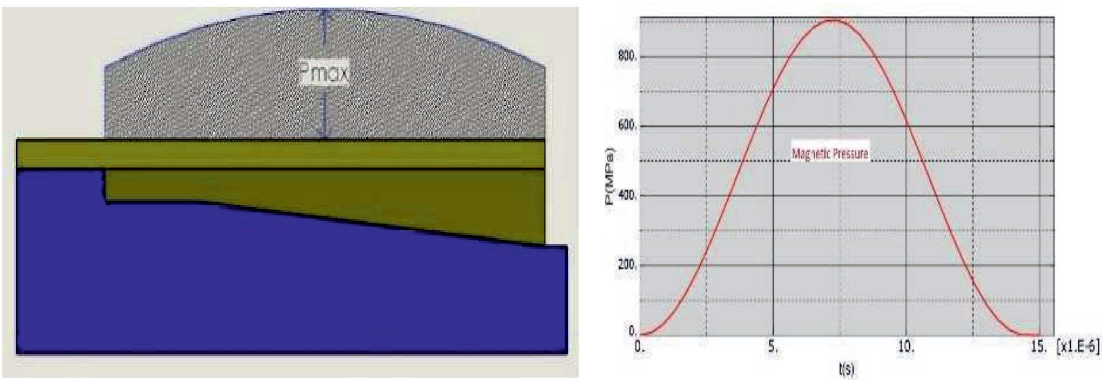

Figure 28.3. Pressure variation along the length of clad and with time.

$$P(magnetic\ pressure) = \frac{B^2}{2 \times \mu}(1 - e^{-2t/s}) \tag{28.2}$$

Johnson-Cook visco-plastic model is chosen to analyze the material behavior during microsecond pulse loading in magnetic pulse welding as material is both temperature and strain-rate sensitive. Johnson-Cook material model [2] is taken, which expresses the flow stress as,

$$\sigma_{flow} = \lfloor A + B\varepsilon^{n} \rfloor \left[1 + C\, ln\left(\varepsilon/\varepsilon_{o}\right)\right] \left[1 - \left(\frac{T - T_{R}}{T_{M} - T_{R}}\right)^{m}\right] \quad (28.3)$$

Where **σ** is the equivalent stress and **ϵ** is the equivalent plastic strain. The material constants are A, B, n, C and m. A is the yield stress of the material under reference conditions, B is the strain hardening constant, n is the strain hardening coefficient, C is the strengthening coefficient of strain rate, and m is the thermal softening coefficient. T91 material Johnson-Cook properties are mentioned in Table 28.1 [1].

Table 28.1. Johnson-Cook properties of T91 material.

A (MPa)	B (MPa)	C	n	m	T_m(K)	T	$\dot{\varepsilon}_{O(S^{-1})}$
445.7	601.1	0.0388	0.186	1.352	1141.8	25	10.52

Dynamic Explicit procedure is adopted for impact analysis and axis-symmetric element CAX3: A3 node axisymmetric triangle is used in the model. Impact velocity and stresses in job piece during stages of impact are shown in the Figure 28.4.

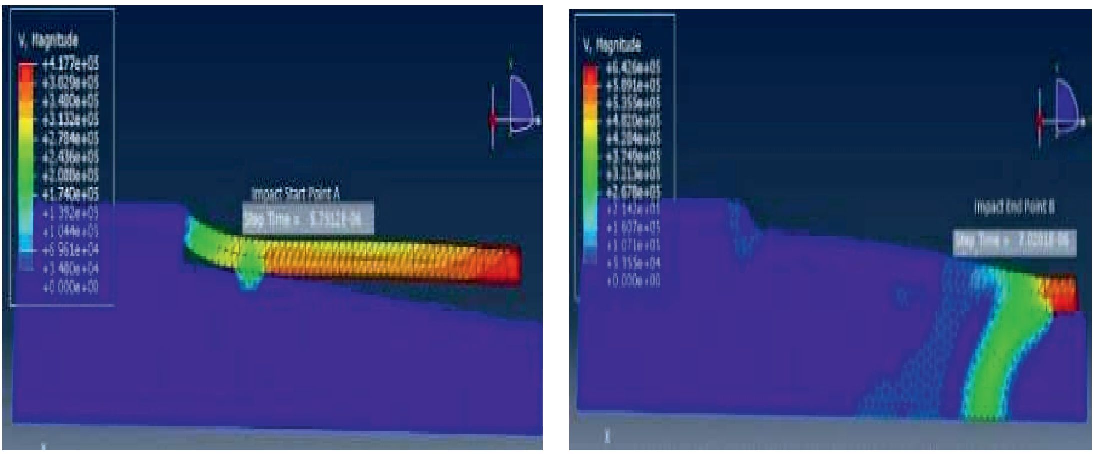

Figure 28.4. Velocity of impact first and last node along the length of clad from fixed edge.

From above figure it is observed that point A of the clad makes first contact at time 5.7 μs and its impact velocity is 350 m/s. End portion of the clad (point B) makes impact with end plug with velocity of 570 m/s at time 7 μs (Figure 28.5).

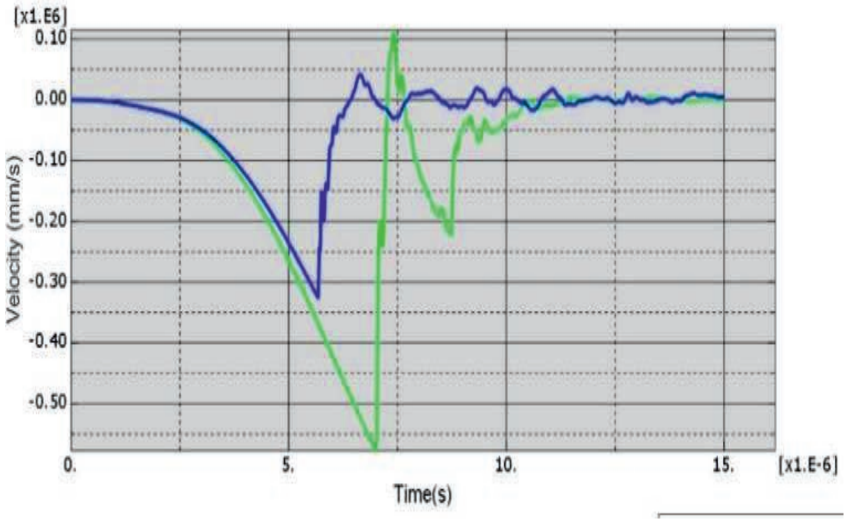

Figure 28.5. Impact velocity.

Minimum impact velocity to achieve successful weld in case of similar materials is recommended by Kore et al. (2010) as

$$U = \sqrt{\frac{\sigma_{TU}}{S}} \tag{28.4}$$

Where U is the threshold velocity (m/s), σTU is the ultimate tensile stress (MPa) and S is the velocity of sound in the material considered (m/s). In the present case minimum velocity of impact for T91 shall be 423 m/s. From the analysis it is found that portion of the clad beyond 6 mm from fixed edge is having velocity of impact more than 430 m/s and hence this zone of impact is expected to achieve successful weld because it is satisfying minimum criteria of impact velocity as recommended by Kore et al. (2010) [2]. Metallography of weld interface for T91 is conducted in the Lab experiment as shown in the Figure 28.6.

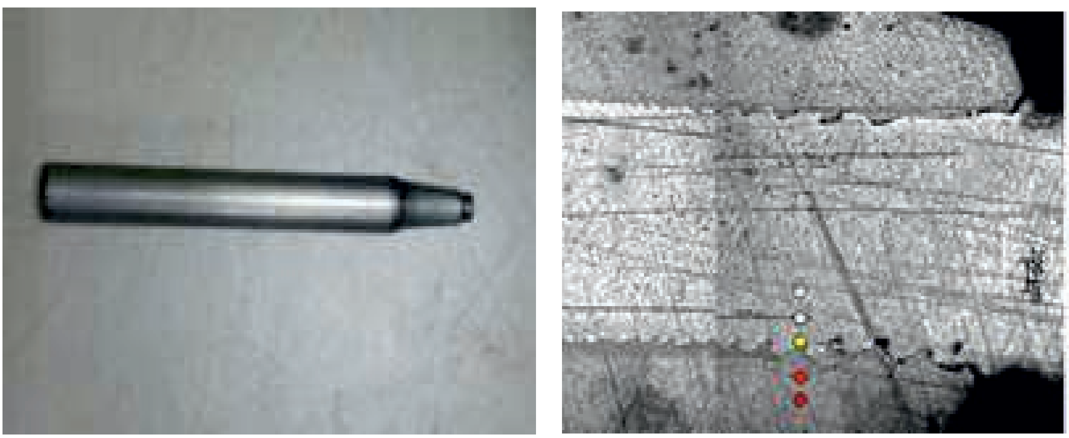

Figure 28.6(a). T91 tube – end plug weld (left) and (b). Welded interface (right).

It is confirmed from the experiment that distinct weld zone / wavy interface is observed beyond initial portion of the clad as was envisaged from the analysis i.e. zone of impact with certain Minimum velocity required for successful weld as stated earlier. Also, too high velocity of impact leads to formation of inter-metallic at the weld interface which subsequently leads to brittle damage of the mating members. On the other hand, at a very low velocity, the jet formed is unable to eliminate the contaminants and oxide layer from the work piece surface leading to an unsuccessful weld.

Numerical simulation can be carried out for determining weld window for successful weld by varying impact angle, input current frequency and input voltage. In future, numerical simulations can be carried out for three dimensional models of the coil and sheets with strong coupling between the electromagnetic and structural code. The impact velocity can be measured and compared with the numerical results to validate the numerical models.

References

[1] Vallourec & Mannesmann Tubes "*The T/P91 Book*" 1999.

[2] S D Kore, P Dhanesh, SV Kulkarni (2010), Numerical modeling of electromagnetic welding, International Journal of Applied Electromagnetics and Mechanics, Volume 32 Issue 1 Pages 1-19 (2010).