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Analytical Estimation of Electromagnetic Pressure, Flyer Impact Velocity, and Welded Joint Length in Magnetic Pulse Welding

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Abstract: Magnetic pulse welding involves the joining of two metallic parts in a solid state by the use of a short and intense electromagnetic impulses and the resulting impact between the parts. The coalesced interface undergoes visco-plastic deformation at a high strain rate and exhibits a wavy shape at a microscopic scale. A practical estimation of the electromagnetic pressure, impact velocity and welded joint length as a function of the process conditions and the electromagnetic coil geometry is required but currently not available. Three novel analytical relations for the estimation of the electromagnetic pressure, impact velocity, and welded joint length for magnetic pulse welding of tubes and sheets, are presented. These relations were developed systematically, following a dimensional analysis, and validated for a wide range of conditions from independent literature. The comparison of the analytically computed results and the corresponding values reported in the literature has illustrated that the proposed analytical relations can be used for the estimation of the electromagnetic pressure and impact velocity for the magnetic pulse welding of tubes and sheets with a good level of confidence. The analytically calculated results for the welded joint length show a little discrepancy with the corresponding experimentally measured values. Further investigations and more experimentally measured results are required to arrive at a more comprehensive analytical relation for the prediction of welded joint length.

Keywords: magnetic pulse welding; dimensional analysis; analytical relations; electromagnetic pressure; impact velocity; joint length

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1. Introduction

Magnetic pulse welding (MPW) of metallic materials involves the application of an intense electromagnetic (EM) pulse for a short duration [1]. The resulting EM force drives the flyer part to impact on the target part, with high velocity, leading to rupture and jetting of the surface impurities and rapid coalescence between the overlapped parts [1]. An advance estimate of the EM pressure and the flyer impact velocity is required to design a suitable process schedule and to assess the joint quality in MPW [2]. The use of comprehensive numerical models [3] and wide-ranging experiments [4] is growing, to improve the insightful understanding of MPW, but these are computationally intensive [5] and time-consuming [6]. A practical framework is needed for a fast and reliable estimate of the EM pressure, flyer impact velocity, and the joint dimensions for a given process schedule to enhance the commercial application of MPW [7].

Computer-based numerical models have been reported for MPW of tubes of similar and dissimilar materials, such as aluminum alloys [8,9], aluminum and copper alloys [10], and aluminum alloys and steel [11], for an EM field and a pressure in the range of 26 to 32 T and 390 to 600 MPa, respectively. The wall thicknesses of these tubes were in the range of 0.5 to 2.0 mm [8–11]. Often, internal supports were used inside the target tubes to enhance

the stiffness and avoid plastic collapse of the tubular assembly due to the high velocity impact of the flyer onto the target [11]. For MPW of similar and dissimilar metallic sheets, the reported values of the EM field and pressure were in the range of 25 to 27 T, and 248 to 290 Mpa, respectively [12,13]. The thickness of these sheets varied in the range of 0.8 to 1.0 mm [12,13]. These investigations have provided a practical knowledge base of the EM field, and pressure to obtain a qualitative joint during MPW of metallic tubes and sheets.

The flyer impact velocity governs the nature of the collision between the parts and the consequent rupture and jetting out of the surface impurities, and the visco-plastic deformation and coalescence of the clean metallic interfaces [14,15]. For MPW of aluminum alloy tubes with steel [11,16,17] and with copper [18] target tubes with wall thicknesses from 0.8 to 1.0 mm, the flyer impact velocity was reported in the range of 140 to 363 m/s. Likewise, the flyer impact velocity was reported in the range of 240 to 458 m/s for MPW of sheets for similar materials such as aluminum alloys [19,20] and for dissimilar materials such as aluminum and steel [21,22], and aluminum and copper [23,24]. The thickness of the sheets was in the range of 1 to 2.5 mm. An increase of the flyer impact velocity for an increased discharge energy [17–22] and the stand-off distance [17,19,22] is also reported.

In contrast to the comprehensive numerical models, efforts are emerging to develop direct analytical relations for the estimation of the EM pressure and flyer impact velocity. For MPW of tubes, simple analytical relations are proposed for the estimation of the EM pressure as a function of discharge energy and coil geometry [25,26] and for the estimation of the flyer impact velocity as a function of the EM pressure and the tube wall thicknesses [26]. Similar relations for the estimation of EM pressure are also discussed for MPW of sheets [27,28]. Although these analytical relations have provided a way forward for a quick estimation of the EM pressure and flyer impact velocity for the MPW process, they have not considered the influence of several important process variables in a comprehensive manner. It is further noteworthy that no efforts have been reported to date on the development of an analytical relation for the estimation of the weld length for MPW of tubes and sheets as a function of the important process variables.

In the present work, novel comprehensive analytical relations were developed for the estimation of EM pressure, flyer impact velocity, and the final welded length along the flyer–target interface for MPW of tubes and sheets using a dimensional analysis. Emphasis is placed on embodying the influence of the key process variables in each case, so that these relations can be used for a quick estimation of the important responses in MPW. The calculated results from the developed analytical relations are examined with the numerically computed and experimentally observed results for MPW of tubes and sheets.

2. Process Mechanics and Theoretical Background

Figure 1 represents a schematic set-up for MPW of tubes with a multi-turn coil and field shaper assembly. The energy is discharged instantaneously through the capacitor bank using a high current switch (S_g). The magnitudes of the net capacitance (C), the total resistance (R_t), and inductance (L_t) govern the initial peak and the damped sinusoidal nature of the discharge energy from the EM coil. The discharge current results in a high intensity EM field and resulting force on the flyer tube that drives the flyer to impact onto the target with a high velocity. A Rogowski coil (Rocoil 1232/X 6121 Integrator, Rocoil Ltd., North Yorkshire, UK) is used to monitor the discharge current (Figure 1). The flyer velocity is measured by a photon doppler velocimetry (PDV) (Modular PDV system Agilent Infinium DSO 90604 6 GHz Oscilloscope with post process Cafeine software; Commissariat à l’Energie Atomique (CEA), France, and PDV modular LeCroy Waverunner 620Z Digital Oscilloscope and Pigtail LPC probe, AMS Technologies Fraunhofer Martinsried, Germany) setup (Figure 1).

The computed EM field is subsequently used to calculate the EM force as:

$$\mathbf{F} = \mathbf{J} \times \mathbf{B} \quad (4)$$

where the induced eddy current density $\mathbf{J}$ is equal to $\nabla \times \mathbf{H}$ and the magnetic flux density $\mathbf{B}$ is equal to $\mu\mathbf{H}$. The computed EM force field over the flyer is considered as an input for the dynamic mechanical analysis, which calculates the flyer impact velocity and the consequent visco-plastic deformation of the flyer–target assembly, following the momentum equilibrium equation:

$$\ddot{x}_i = (F_i/m) + b_i \quad (5)$$

where $\ddot{x}_i$ and b_i are the final and initial acceleration and F_i is the applied force at the i th point of the flyer with mass m . The numerical solution of Equation (5) for the calculation of the flyer impact velocity and the deformation of the flyer–target assembly is also challenging as it requires a fairly accurate estimation of the dynamic mechanical behavior of the materials at a high strain rate [35]. As the flyer–target assembly undergoes a progressive deformation along the overlapped length, a fine mesh of the solution domain with a large number of discrete elements is a requisite [33,37,38]. The transient change of the EM field as the flyer moves away from the coil further requires a coupled field analysis, which is often neglected [39]. Recent efforts involved an independent calculation of the EM field and pressure at considering the deformed flyer–target assembly at discrete time-steps, which required a significant volume of computational time and resources [33].

In summary, the inherent interrelated phenomena in MPW are rather complex and a true consideration of these phenomena, by means of a fully-fledged numerical process model, is extremely challenging and demands substantial computational resources [11,25]. A recourse is to develop appropriate analytical relations to calculate the primary responses in MPW, such as the EM field and pressure, the flyer impact velocity and the expected flyer–target bonded length. The available analytical relations depict a need for a systematic approach for the development of comprehensive analytical relations that can account for the effect of the most influential process variables in MPW.

3. Analytical Formulation

The analytical formulations for the EM pressure, flyer impact velocity, and flyer–target welded length were developed, considering the effect of the related variables. The dimensional analysis was employed to formulate these analytical relations due to the presence of several physical phenomena and their complex interactions, which cannot always be expressed by closed-form mechanistic relationships. The computed values from these relations are examined with the corresponding results from independent literature and presented in the next section.

3.1. Formulation for the EM Pressure

The EM pressure (p) is influenced primarily by the EM field, the magnetic flux density and the induced eddy current density as shown in Equation (4). The EM field is influenced by the nature and magnitude of the discharge energy (U), the coil geometry, and the air gap between the coil and the flyer [40–42]. To achieve a higher concentration of the EM pressure, an assembly of a multi-turn coil and a field shaper are often utilized [22,43–45]. A direct analytical relation is therefore required to compute the EM pressure as a function of the important influencing variables.

A dimensional analysis using the Buckingham π -theorem is therefore undertaken to develop a relationship for EM pressure as a function of the important variables [46]. Since the MPW of tubes and sheets uses, respectively, circular and flat coils with different geometry and a different effective cross-sectional area, the relationships for the corresponding EM pressure are developed separately [2,7]. Table 1 presents ten variables and their dimensions in the MLTI system, which are considered for the dimensional analysis of EM pressure

for MPW of tubes. For ten variables and four fundamental dimensions, six π terms are obtained as:

$$\pi_1 = \frac{p l_c^3}{U} \quad (6)$$

$$\pi_2 = \frac{\mu_f l_c}{L_t} \quad (7)$$

$$\pi_3 = n \quad (8)$$

$$\pi_4 = \frac{\tau}{f} \quad (9)$$

$$\pi_5 = \frac{e_c}{l_c} \quad (10)$$

$$\pi_6 = \frac{w_i}{l_c} \quad (11)$$

Table 1. Variables and their corresponding dimensions in the MLTI system for dimensional analysis of the EM pressure for MPW of tubes.

Variable	Symbol	Dimension
EM pressure (Pa)	p	$ML^{-1}T^{-2}$
Discharge energy (J)	U	ML^2T^{-2}
Magnetic permeability of flyer (H/m)	μ_f	$MLT^{-2}I^{-2}$
Number of turns	n	-
Length of coil (m)	l_c	L
Thickness of coil (m)	e_c	L
Total inductance (H)	L_t	$ML^2T^{-2}I^{-2}$
Discharge frequency (Hz)	f	T^{-1}
Damping constant (s^{-1})	τ	T^{-1}
Field shaper inner length (m)	w_i	L

The derivation of the π terms is presented in Appendix A.

The EM pressure (p) is directly proportional to both the discharge energy (U) and its frequency (f) [11,47,48]. A higher value of the equivalent inductance of the discharge circuit (L_t) will result in a greater loss of energy and will reduce the generated EM field and pressure [45,49]. The magnetic permeability of the flyer material (μ_f) close to the magnetic permeability of the air (μ_0) results in a stronger EM field and resulting EM pressure for a given discharge energy and coil geometry [28,41,50]. An increase in the damping constant will lead to a reduced intensity of the discharge current (U) and resulting EM pressure (p). The EM pressure is also proportional to the square of the number of turns of a coil [9,41,44]. The increase in length (l_c) and thickness (e_c) of a coil reduces the discharge current density, and the resulting EM field and pressure [51]. In contrast, a smaller length of the field shaper inner surface (w_i) leads to a higher current density and resulting EM field and pressure [8].

The above discussion shows that the dimensionless variable for the EM pressure (π_1) is directly proportional to π_2 and the square of π_3 , which embody the effect of the magnetic permeability of the flyer and the number of turns of the coil, respectively. The EM pressure (π_1) is also inversely proportional to π_4 , π_5 , and π_6 , which embody the effect of the damping constant of the discharge energy, the coil thickness, and the effective length of the field shaper, respectively. The six π terms are therefore expressed as:

$$\pi_1 = \left(\frac{\pi_2 \pi_3^2}{\pi_4 \pi_5} \right) \left(\frac{1}{\sqrt{\pi_6}} \right) \quad (12)$$

Equation (12) can be written further in terms of the actual process variables as:

$$p = C_f \left(\frac{U \mu_f f n^2}{l_c e_c L_t \tau} \right) \quad (13)$$

The term C_f in Equation (13) is equal to $\sqrt{l_c/w_c}$, which is an inverse of π_6 and refers to a “geometric field concentration factor”. An increase of C_f will result in higher EM pressure. For a coil geometry without a field shaper, the term C_f is equal to unity.

Equations (12) and (13) cannot be used for MPW with flat coils of rectangular cross-sections (Figure 2), which are commonly employed for the joining of metallic sheets [52]. Unlike the coil length (l_c) and number of turns (n) in the case of a circular coil, the surface area [thickness (e_c) $\times$ width (w_c)] of a flat coil is responsible to apply the EM field and pressure on the flyer sheet. Moreover, the use of field shaper for MPW of sheets is scarce. Accordingly, eight variables are considered to estimate the EM pressure for MPW of sheets with flat coils as shown in Table 2. For eight variables and four fundamental dimensions, four π terms are obtained as:

$$\pi_7 = \frac{pw_c^3}{U} \quad (14)$$

$$\pi_8 = \frac{w_c}{e_c} \quad (15)$$

$$\pi_9 = \frac{\mu_f w_c}{L_t} \quad (16)$$

$$\pi_{10} = \frac{\tau}{f} \quad (17)$$

Figure 2. Schematic geometry and dimensions of a flat linear coil for MPW of sheets.

Table 2. Variables and their corresponding dimensions in the MLTI system for dimensional analysis of the EM pressure for MPW of sheets.

Variable	Symbol	Dimension
EM pressure (Pa)	p	$ML^{-1}T^{-2}$
Discharge energy (J)	U	ML^2T^{-2}
Magnetic permeability of flyer (H/m)	μ_f	$MLT^{-2}I^{-2}$
Width of coil (m)	w_c	L
Thickness of coil (m)	e_c	L
Total inductance (H)	L_t	$ML^2T^{-2}I^{-2}$
Discharge frequency (Hz)	f	T^{-1}
Damping constant (s^{-1})	τ	T^{-1}

The derivation of the π terms is presented in Appendix B.

The EM pressure (p) for flat coils increases with a decrease of the width (w_c) and the thickness (e_c) of the coil [53]. The dimensionless EM pressure (π_7) is therefore considered as directly proportional to π_9 , which accounts for the magnetic permeability of the flyer, and inversely proportional to π_8 and π_{10} , which embody the effect of the coil width and

the damping constant of the discharge energy, respectively. The four π terms are therefore expressed as:

$$\pi_7 = \left(\frac{\pi_9}{\pi_8 \pi_{10}} \right) \quad (18)$$

Equation (18) can be expressed further in terms of the process variables as:

$$p = C_L \left(\frac{U \mu_f e_c f}{w_c^3 L_t \tau} \right) \quad (19)$$

where C_L refers to a “concentration length factor” and is expressed as the ratio l_{of}/l_{rc} where l_{of} and l_{rc} are the active (l_{of}) and the non-active (l_{rc}) segments of a flat coil (Figure 2).

A comparison of Equations (13) and (19) shows the presence of a factor (C_f and C_L) to account for the effect of the concentration of the EM field due to the presence of a field shaper for a circular coil and an inherent convergent geometry of a flat coil, respectively. Equations (13) and (19) distinguish themselves from similar expressions reported in the literature by the fact that the effect of the coil geometry and the discharge current frequency and its damping nature are included, which are important for the estimation of the EM pressure [25,28,40].

3.2. Formulation for the Impact Velocity

The flyer impact velocity (v_i) is influenced primarily by the EM pressure (p), the stand-off distance (s), the wall thickness of flyer (e_f), and density (ρ_f) of the flyer material [12,14,15,48,54]. A numerical solution of Equation (5) can compute the flyer impact velocity but will require huge computational resources and time. An analytical estimation of the flyer impact velocity can quickly realize the feasibility of given MPW process conditions [25–28,40,41]. A dimensional analysis is therefore undertaken to identify a suitable relation for the flyer impact velocity as a function of the important variables. Table 3 presents five variables and their dimensions in the MLT system, for the dimensional analysis. Considering five variables and three fundamental dimensions, two π terms are obtained as:

$$\pi_{11} = v_i \sqrt{\frac{\rho_f}{p}} \quad (20)$$

$$\pi_{12} = \frac{s}{e_f} \quad (21)$$

Table 3. Variables and their dimensions in the MLT system for the dimensional analysis of the flyer impact velocity for MPW of tubes and sheets.

Variable	Symbol	Dimension
EM pressure (Pa)	p	$ML^{-1}T^{-2}$
Flyer impact velocity (m/s)	v_i	LT^{-1}
Flyer material density (kg/m^3)	ρ_f	ML^{-3}
Stand-off distance (m)	s	L
Thickness of flyer (m)	e_f	L

The derivation of the π terms is shown in Appendix C.

The variable π_{11} presents the flyer impact velocity in a dimensionless form for an EM pressure and a flyer material. Both an increase of the stand-off distance and a decrease of the flyer thickness are likely to increase the flyer impact velocity. Thus, a direct relation between the dimensionless variables π_{11} and π_{12} can be constructed as:

$$\pi_{11} = \kappa(\pi_{12}) \quad (22)$$

where, κ represents a linear function. Based on the further trial and error calculations, the flyer impact velocity is expressed in terms of the MPW process variables as:

$$v_i = \sqrt{\frac{p}{\rho_f}} \left(\frac{s}{e_f} \right) \quad (23)$$

Similar analytical expressions for the estimation of the flyer impact velocity are reported in literature [25,28,40,41]. However, the reported expressions in literature did not consider the effect of the stand-off distance [25,40,41] and the flyer thickness [28]. Furthermore, a systematic approach to develop the analytical relation for the estimation of the flyer impact velocity has also not been reported in the contemporary literature.

3.3. Formulation for the Joint Length

The joint length is referred to the intimate contact along the flyer–target interface as a result of the EM pressure of the flyer, its progressive impact on the target and the consequent visco-plastic deformation of the flyer–target assembly [3,5]. The joint length is often observed using microscopy and measured by means of peel tests [2,7,33]. The finite element method based computational models for MPW have construed the joint length by examining the segment of the flyer that is in close contact with the target along the flyer–target interface [2,5,7]. It is therefore quite difficult, or even impossible, to identify the exact length of the joint for MPW of tubes and sheets and the difficulty is exacerbated further due to the microscopic wavy nature of the joint interface [10,14]. A simpler approach is adopted here to estimate the joint length as a function of the flyer impact angle (α) and impact velocity (v_i), and the target material density (ρ_t) and its flexural rigidity (EI) [55–57]. Table 4 presents these five variables and their dimensions in the MLT system for the dimensional analysis. Considering five variables and three fundamental dimensions, two π terms are obtained as:

$$\pi_{13} = \sqrt{v_i} \frac{\rho_t^{1/4}}{\{EI\}^{1/4}} W_L \quad (24)$$

$$\pi_{14} = \alpha \quad (25)$$

Table 4. Variables and their corresponding dimensions in the MLT system for the dimensional analysis of the weld joint length (W_L) for MPW of tubes and sheets.

Variable	Symbol	Dimension
Joint length (m)	W_L	L
Flyer impact velocity (m/s)	v_i	LT^{-1}
Impact angle (deg)	α	-
Density of target material (kg/m^3)	ρ_t	ML^{-3}
Flexural rigidity of target ($Pa \cdot m^4$)	EI	ML^3T^{-2}

The derivation of the π -terms is presented in Appendix D.

The variable π_{13} embodies the welded length in a dimensionless form for a flyer impact velocity, and the material density and flexural rigidity of a target. A higher value of the initial impact angle is likely to result in greater impact velocity and higher welded segment [5,10,55,56]. Thus, a direct relation between the π_{13} and π_{14} is conceived as follows:

$$\pi_{13} = \gamma(\pi_{14}) \quad (26)$$

where, γ represents a linear function. Based on further trial and error calculations, the welded length/segment is expressed as

$$W_L = \frac{(EI)^{1/4} \alpha}{(\rho_t)^{1/4} \sqrt{v_i}} \quad (27)$$

Equation (27) provides a recourse for a quick analytical estimation of the welded joint length for MPW of tubes and sheets for a given value of the maximum impact velocity of the flyer and the initial flyer impact angle, the target material density and the rigidity of the target geometry. To the best of our knowledge, this is the first attempt of a direct analytical estimation of the welded joint length for MPW of tubes and sheets. Indeed, the primary emphasis is a simplistic approach and a first-hand estimation rather than a complex approach that may require extensive computational resources.

4. Computed Results

Equations (13), (19), (23) and (27) are used to compute the EM pressure, flyer impact velocity, and welded joint length for a range of conditions for MPW of tubes and sheets from reported literature. The analytically computed values are compared with the corresponding experimentally measured or theoretically computed results as reported in the literature.

4.1. Estimation of the EM Pressure

Tables 5 and 6 show the variables and their values that are used for the calculation of the EM pressure for MPW of tubes and sheets using Equations (13) and (19), respectively. The corresponding reference for each set of data is also indicated in the Tables 5 and 6. For MPW of tubes, the types of coil assembly include single-turn coils [58,59], single-turn coils with a field shaper [10], multi-turn coils [9], and multi-turn coils with a field shaper [7,11,25,33]. In contrast, Table 6 includes the variables for linear flat coils for MPW of sheets. The flyer and the target materials for each case are shown in the Tables 5 and 6.

Table 5. Values used for calculation of the EM pressure (p) for MPW of tubes.

Variables (Units)	Values					
	[58]	[7,33]	[59]	[11,25]	[9]	[10]
U (kJ)	15	14, 16	12	6	20.667	22
μ_f ($\mu\text{H}/\text{m}$)	1.256	1.243		1.256		
n	1	5	1	8	7	1
l_c (m)	0.031	0.055	0.0381	0.0916	0.045	0.03
e_c (m)	0.0518	0.09075	0.0896	0.0485	0.055	0.06
L_t (μH)	0.16	0.55	0.10	1.09	1.50	0.0795
f (kHz)	19.7	17.0	19.2	16.0	6.89	21.5
τ (s^{-1})	8333	13003	6757	9500	5035	15274
w_i (m)	-	0.008	-	0.015	-	0.015
C_f	1	2.62	1	2.47	1	1.414
Flyer	AA2017	Cu-DHP	AA2024	AA6060	AA6061	AA2024
Target	SS304	11SMnPb30	-	AISI1045	AA6061	Cu

Data not provided in references are presumed rationally.

Table 6. Values used for calculation of the EM pressure (p) for MPW of sheets.

Variables (Unit)	Values		
	[2]	[28]	[13]
U (kJ)	10, 16	3.25	10.7
μ_f ($\mu\text{H}/\text{m}$)		1.256	
w_c (m)	0.008	0.01	0.01
e_c (m)	0.0028	0.015	0.008
L_t (μH)	0.181	0.162	0.2649
f (kHz)	18.5	40	25.4
τ (s^{-1})	11049	21140	6983
C_L	0.22	0.40	0.20
Flyer	AA5754	AA5005	AA1060
Target	DC04 steel	AA6060	Cu

Data not provided in references are presumed rationally.

Figure 3a,b shows the analytically calculated versus the corresponding reported values of the EM pressure for MPW of tubes and sheets, respectively. The reference number for

each data set is also included in Figure 3a,b. Figure 3a shows that the analytically calculated values of the EM pressure for MPW of tubes are in similar order of magnitude with the corresponding reported values with the range of deviations from 1% to 37% considering most of the cases. For example, the analytically computed values of the EM pressure for MPW of AA2017 flyer and SS304 target tubes [58] and electromagnetic forming of AA2024 tubes [59] are 174 and 127 MPa, respectively. The corresponding reported values are 240 [58] and 185 MPa [59], respectively. Likewise, the analytically computed values of the EM pressure for MPW of AA6061 flyer and target tubes [9], AA2024 flyer and Cu target tubes [10], and Cu-DHP flyer and 11SMnPb30 steel target tubes [7,33] are close to their corresponding reported values as indicated in Figure 3a. These analytically computed values also show that Equation (13) can take into account the effect of different MPW process conditions and coil types for the calculation of the EM pressure. The discrepancy between the analytically computed values using Equation (13) and the corresponding reported values in the literature are attributed to the fact that Equation (13) cannot account for the transient nature of the process.

Figure 3. Analytically calculated and the corresponding reported values of the EM pressure (p) for MPW of (a) tubes and (b) sheets. The square and cross symbols indicate that the corresponding value(s) from the literature are computed numerically and analytically. Details of the process conditions and coil geometry details are provided in Tables 5 and 6 for tubes and sheets, respectively. Numerically computed results are taken from references [2,7,9–11,13,33,58]. Analytically computed results are taken from references [25,28,59].

Figure 3b shows that the analytically calculated values of the EM pressure for MPW of sheets using Equation (19). For example, the analytically computed EM pressures for MPW of AA5754 and DC04 steel sheets [2] using a linear coil with a rectangular cross-section are found to be 139 and 223 Mpa for a discharge energy of 10 and 16 kJ, respectively. The corresponding numerically calculated values are 85 and 118 Mpa, respectively [2]. The overall range of deviations between the analytically calculated and the corresponding reported values from the literature lie between 15% and 38%. The discrepancy between the analytically calculated and the corresponding numerically computed values [2] is attributed to the ability of the comprehensive numerical models to consider the evolution of the EM field and its effect on the EM pressure, which could not be considered by Equation (19). A slight over-estimation is noted for the analytically calculated EM pressure for MPW of aluminum and Cu sheets [13] and between aluminum [28] sheets. The discrepancy between the analytically computed values and the corresponding reported values can further be attributed to the inherent assumption of a uniform cross-section of the coil geometry in contrast to its variable cross-section in reality. Overall, Figure 3a,b shows that Equations (13) and (19) can provide a reasonable estimation of the flyer EM pressure for MPW of tubes and sheets for a range of process conditions and coil geometries.

4.2. Estimation of the Flyer Impact Velocity

Table 7 shows the variables and their values that are used for the calculation of the flyer impact velocity for MPW of tubes and sheets using Equation (23). The corresponding reference for each data set is indicated in Table 7. The values of the EM pressure in Table 7 are calculated using Equations (13) and (19) for MPW of tubes and sheets, respectively. The other variables in Table 7 include the flyer wall thickness, the flyer material density and the stand-off distance between the flyer and the target, which are required for Equation (23).

Table 7. Values used for calculation of the flyer impact velocity (v_i).

Variables (Units)	Values							
	MPW of Tubes					MPW of Sheets		
	[58]	[7,33]	[11,25]	[9]	[10]	[2]	[28]	[13]
p (MPa)	174	548, 626	413	436	384	139, 223	286	295
s (m)	0.00272	0.001	0.0014	0.0025	0.002	0.0012	0.00125	0.002
ρ_f (kg/m ³)	2770	8900	2700	2700	2700	2670	2700	2700
e_f (m)	0.001	0.00089	0.002	0.0015	0.00124	0.0005	0.001	0.001

Data not provided in references are presumed rationally.

Figure 4a,b shows the analytically calculated versus the corresponding reported values of the flyer impact velocity for MPW of tubes and sheets, respectively. The corresponding reference number for each data set is also included in Figure 4a,b. Figure 4a shows that the analytically calculated values of the flyer impact velocity for MPW of tubes are in very good agreement with the corresponding values reported in the literature. For example, the analytically computed values of the flyer impact velocity for MPW of Cu-DHP flyer and 11SMnPb30 steel target tubes [7], AA6060 flyer and AISI1045 steel target tubes [11] and Cu-DHP flyers and 11SMnPb30 steel target tubes [33] are 279, 273, and 298 m/s, respectively. The corresponding reported values are 300 m/s [7], 320 m/s [11], and 333 m/s [33], respectively. For a slightly higher range of discharge energies, the analytically computed values of the flyer impact velocity for MPW of AA6061 flyer and target tubes [9], AA2024 flyer and Cu target tubes [10], and AA2017 flyer and SS304 target tubes [58] are 669, 608, and 681 m/s, respectively. The corresponding reported values are 660 m/s [9], 625 m/s [10], and 725 m/s [58], respectively.

Figure 4. Analytically calculated and the corresponding reported values of flyer impact velocity (v_i) for MPW of (a) tubes and (b) sheets. The square, cross, and plus symbols depict that the corresponding value(s) from the literature are computed numerically and analytically, as well as measured experimentally. Details of the process conditions and coil geometry details are provided in

Table 7. Numerically computed results are taken from references [2,7,9–11,13,33,58]. Analytically computed results are taken from references [25,28]. Experimentally measured data are taken from references [2,7,11,25,33].

Figure 4b shows that the analytically calculated values of the flyer impact velocity for MPW of sheets are slightly higher in comparison to the corresponding values reported in literature. For example, the analytically computed values of the flyer impact velocity for MPW of AA5754 flyer and DC04 steel target sheets [2], AA1060 flyer and Cu target sheets [13], and AA5005 flyer and AA6061 target sheets [28] are 547 and 693 m/s, and 660 and 407 m/s, respectively. The two values for [2] correspond to two different values of the EM pressure. The corresponding reported values are 373 m/s and 449 m/s [2], 500 m/s [13] and 325 m/s [28], respectively. The slight discrepancy between the analytically calculated and the corresponding reported values [2,13,28] is attributed primarily to the over-estimation of the EM pressure values using Equation (19) as shown in Figure 3b.

4.3. Estimation of the Joint Length

Table 8 show the variables and their corresponding values that are used to calculate the joint length for MPW of tubes and sheets using Equation (27). The respective reference for each data set is shown in Table 8. The values of the flyer impact velocity in Table 8 are obtained analytically using Equation (23). The other important variables in Table 8 include the wall thickness and the flexural rigidity of the target tubes and sheets and the initial impact angle between the flyer and the target. The unit of the impact angle is considered in radian for calculations.

Table 8. Values used for the calculation of the joint length (W_L).

Variables (Unit)	Values			
	MPW of Tubes		MPW of Sheets	
	[58]	[7,33]	[2]	[13]
v_i (m/s)	681	279, 298	547, 693	660
α (deg)	8	3.82	3.43	4.57
ρ_t (kg/m ³)	8030	7800	7870	8920
EI (Pa · m ⁴)	1600	957	6833	6000

Data not provided in references are assumed rationally.

Figure 5 shows the analytically calculated values versus the corresponding reported values of the welded joint length for MPW of tubes and sheets. The corresponding reference number for each data set is also shown in Figure 5. Overall, Figure 5 indicates a slight under-estimation of the welded joint lengths from Equation (23) in comparison with the corresponding values reported in literature for both MPW of tubes and sheets. For example, the analytically computed joint length for MPW of AA2017 flyer and SS304 target tubes is 3.57 mm in comparison to 4.56 mm, which is observed experimentally [58]. Likewise, the analytically computed and the corresponding reported values of the welded joint lengths for MPW of AA5754 flyer and DC04 steel target sheets are 2.46 and 2.70 mm [2], and for MPW of AA1060 flyer and Cu target sheets are 2.81 and 4 mm [13]. The somewhat larger discrepancy between the analytically calculated and the corresponding reported welded joint lengths for MPW of Cu-DHP flyer and 11SMnPb30 steel target [7,33] tubes is attributed to the influence of multi-turn coils with variable cross-sections, which could not be accounted for truly by Equation (23) for the calculation of the flyer impact velocity.

Figure 5. Analytically calculated and the corresponding experimentally measured (from the literature, as shown against each point) values of the joint length (W_L) for MPW of tubes and sheets. Details of the process conditions and coil geometry details are provided in Table 8. Experimentally measured data are taken from references [2,7,13,33,58].

5. Summary and Conclusions

A set of analytical relations were developed in the present work based on a dimensional analysis for quick estimations of the EM pressure, the flyer impact velocity, and the welded joint lengths for MPW of tubes and sheets. The analytical relations are used to compute the corresponding values for a wide range of MPW conditions, which are reported in the literature. The analytically computed results are compared with the corresponding values from the literature, which are reported based on either experimental measurements and/or theoretical calculations. In general, the proposed analytical relationships for the estimation of the EM pressure and flyer impact velocity are found to estimate the corresponding values for MPW of tubes and sheets fairly. However, the proposed analytical relation for the estimation of the welded joint length appears to need further improvement. Based on the current work, the following conclusions are drawn.

- A systematic approach is presented here to develop novel, easy-to-use analytical relations for the estimation of the EM pressure, the flyer impact velocity, and the welded joint length for MPW of tubes and sheets following a dimensional analysis.
- The analytical relation of the EM pressure for MPW of tubes and sheets is developed separately, due to the respective use of circular and flat coils with a different geometry and a different effective cross-sectional area.
- The effect of the concentration of the EM field due to the presence of a field shaper for a circular coil and an inherent convergent geometry of a flat coil are also included.
- The proposed analytical relations could provide a reasonable estimation of the EM pressure and flyer impact velocity for MPW of tubes and sheets for a range of commonly used process conditions.
- The proposed analytical relation for the joint length is found to under-estimate the welded joint length, especially for MPW using complex multi-turn coil geometries, with and without a field shaper.
- Overall, the proposed analytical relations could consider the effect of the key MPW variables for the calculations of three important process characteristics, which can be of immense help for a quick design of practical MPW schedules.

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Appendix A

The dimensional analysis for the EM pressure (p) for MPW of tubes involves ten variables (Table 1) with four fundamental dimensions M , L , T , and I ; thus, six π terms are constituted. Considering four repeating variables as f , l_c , L_t , and U (Table 1), the first π term, π_1 is expressed as:

$$\pi_1 = [(U)^a (l_c)^b (L_t)^c (f)^d] (p) \quad (A1)$$

Equation (A1) can be written further in dimensional form as:

$$[M^0 L^0 T^0 I^0] = [M^1 L^2 T^{-2}]^a [L^1]^b [M^1 L^2 T^{-2} I^{-2}]^c [T^{-1}]^d [M^1 L^{-1} T^{-2} I^0] \quad (A2)$$

which yields the values of the exponents as ($a = -1$, $b = 3$, $c = 0$, and $d = 0$). The π_1 term is therefore expressed as $\pi_1 = [p(l_c)^3]/U$. The second π term, π_2 is expressed as:

$$\pi_2 = [(U)^a (l_c)^b (L_t)^c (f)^d] (\mu_f) \quad (A3)$$

which can be written further in a dimensional form as:

$$[M^0 L^0 T^0 I^0] = [M^1 L^2 T^{-2}]^a [L^1]^b [M^1 L^2 T^{-2} I^{-2}]^c [T^{-1}]^d [M^1 L^1 T^{-2} I^{-2}] \quad (A4)$$

and the values of the exponents are obtained as ($a = 0$, $b = 1$, $c = -1$ and $d = 0$). The π_2 term is therefore expressed as $\pi_2 = (\mu_f l_c)/L_t$. The third π term, π_3 is considered as:

$$\pi_3 = [(U)^a (l_c)^b (L_t)^c (f)^d] (n) \quad (A5)$$

and in a dimensional form as:

$$[M^0 L^0 T^0 I^0] = [M^1 L^2 T^{-2}]^a [L^1]^b [M^1 L^2 T^{-2} I^{-2}]^c [T^{-1}]^d [M^0 L^0 T^0 I^0] \quad (A6)$$

resulting in the values of the exponents as ($a = 0$, $b = 0$, $c = 0$ and $d = 0$). The π_3 term is therefore expressed as $\pi_3 = n$. The fourth π term, π_4 is expressed as:

$$\pi_4 = [(U)^a (l_c)^b (L_t)^c (f)^d] (\tau) \quad (A7)$$

and in a dimensional form as:

$$[M^0 L^0 T^0 I^0] = [M^1 L^2 T^{-2}]^a [L^1]^b [M^1 L^2 T^{-2} I^{-2}]^c [T^{-1}]^d [M^0 L^0 T^{-1} I^0] \quad (A8)$$

which yields the values of the exponents as ($a = 0$, $b = 0$, $c = 0$ and $d = -1$). The π_4 term is therefore expressed as $\pi_4 = \tau/f$. The fifth π term, π_5 is considered as:

$$\pi_5 = [(U)^a (l_c)^b (L_t)^c (f)^d] (e_c) \quad (A9)$$

and in a dimensional form as:

$$[M^0 L^0 T^0 I^0] = [M^1 L^2 T^{-2}]^a [L^1]^b [M^1 L^2 T^{-2} I^{-2}]^c [T^{-1}]^d [M^0 L^1 T^0 I^0] \quad (A10)$$

The corresponding values of the exponents are obtained as ($a = 0$, $b = -1$, $c = 0$ and $d = 0$) and the π_5 term is expressed as $\pi_5 = e_c/l_c$. The last π term, π_6 is written as:

$$\pi_6 = [(U)^a (l_c)^b (L_t)^c (f)^d] (w_i) \quad (A11)$$

and in a dimensional form as:

$$[M^0 L^0 T^0 I^0] = [M^1 L^2 T^{-2}]^a [L^1]^b [M^1 L^2 T^{-2} I^{-2}]^c [T^{-1}]^d [M^0 L^1 T^0 I^0] \quad (A12)$$

The corresponding values of the exponents are obtained as ($a = 0$, $b = -1$, $c = 0$ and $d = 0$) and the π_5 variable is expressed as $\pi_6 = w_i/l_c$.

Appendix B

The dimensional analysis for the EM pressure (p) for MPW of sheets involves eight variables (Table 2) with four fundamental dimensions M, L, T and I; thus, four π terms are considered. Considering the four repeating variables as f , L_t , U , and w_c (Table 2), the first π term π_7 is expressed as:

$$\pi_7 = [(U)^a (w_c)^b (L_t)^c (f)^d] (p) \quad (A13)$$

and in a dimensional form as:

$$[M^0 L^0 T^0 I^0] = [M^1 L^2 T^{-2}]^a [L^1]^b [M^1 L^2 T^{-2} I^{-2}]^c [T^{-1}]^d [M^1 L^{-1} T^{-2} I^0] \quad (A14)$$

which results in the values of the exponents as ($a = -1$, $b = 3$, $c = 0$ and $d = 0$) and the π_7 term as $\pi_7 = [p(w_c)^3]/U$. The second π term, π_8 is expressed as:

$$\pi_8 = [(U)^a (w_c)^b (L_t)^c (f)^d] (e_c) \quad (A15)$$

and in dimensional form as:

$$[M^0 L^0 T^0 I^0] = [M^1 L^2 T^{-2}]^a [L^1]^b [M^1 L^2 T^{-2} I^{-2}]^c [T^{-1}]^d [M^0 L^1 T^0 I^0] \quad (A16)$$

which results in the values of the exponents as ($a = 0$, $b = -1$, $c = 0$ and $d = 0$). The term π_8 is therefore expressed as $\pi_8 = w_c/e_c$. The third π term, π_9 is considered as:

$$\pi_9 = [(U)^a (w_c)^b (L_t)^c (f)^d] (\mu_f) \quad (A17)$$

and in dimensional form as:

$$[M^0 L^0 T^0 I^0] = [M^1 L^2 T^{-2}]^a [L^1]^b [M^1 L^2 T^{-2} I^{-2}]^c [T^{-1}]^d [M^1 L^1 T^{-2} I^{-2}] \quad (A18)$$

The corresponding values of the exponents are ($a = 0$, $b = 1$, $c = -1$ and $d = 0$) and the term π_9 is therefore written as $\pi_9 = (\mu_f w_c)/L_t$. The fourth π term, π_{10} is expressed as:

$$\pi_{10} = [(U)^a (w_c)^b (L_t)^c (f)^d] (\tau) \quad (A19)$$

and in a dimensional form as:

$$[M^0 L^0 T^0 I^0] = [M^1 L^2 T^{-2}]^a [L^1]^b [M^1 L^2 T^{-2} I^{-2}]^c [T^{-1}]^d [M^0 L^0 T^{-1} I^0] \quad (A20)$$

The corresponding values of the exponents are ($a = 0$, $b = 0$, $c = 0$ and $d = -1$) and the term π_{10} is written as $\pi_{10} = \tau/f$.

Appendix C

The dimensional analysis for the flyer impact velocity (v_i) includes five variables (Table 3) with three fundamental dimensions M, L and T. Two π terms are therefore formed. Considering three repeating variables as p , ρ_f and e_f (Table 3), the first π term π_{11} is given as

$$\pi_{11} = [(p)^a(\rho_f)^b(e_f)^c](v_i) \quad (A21)$$

and in dimensional form as:

$$[M^0L^0T^0] = [M^1L^{-1}T^{-2}]^a[M^1L^{-3}]^b[L^1]^c[M^0L^1T^{-1}] \quad (A22)$$

The corresponding values of the exponents are obtained as ($a = -1/2$, $b = 1/2$ and $c = 0$) and the term π_{11} is written as $\pi_{11} = (v_i) [(\rho_f)^{1/2}(p)^{1/2}]$. The second π term π_{12} is written as:

$$\pi_{12} = [(p)^a(\rho_f)^b(e_f)^c](s) \quad (A23)$$

and in a dimensional form as

$$[M^0L^0T^0] = [M^1L^{-1}T^{-2}]^a[M^1L^{-3}]^b[L^1]^c[M^0L^1T^0] \quad (A24)$$

The corresponding values of the exponents are obtained as ($a = 0$, $b = 0$ and $c = -1$) and the term π_{12} is written as $\pi_{12} = s/e_f$.

Appendix D

The dimensional analysis for the joint length includes five variables (Table 4) with three fundamental dimensions M, L, and T that suggests considering two π terms. Considering three repeating variables as (EI) , ρ_t and v_i (Table 4), the first π term π_{13} is given as:

$$\pi_{13} = [(v_i)^a(\rho_t)^b(EI)^c](W_L) \quad (A25)$$

and in a dimensional form as:

$$[M^0L^0T^0] = [L^1T^{-1}]^a[M^1L^{-3}]^b[M^1L^3T^{-2}]^c[M^0L^1T^0] \quad (A26)$$

The corresponding values of the exponents are obtained as ($a = 1/2$, $b = 1/4$ and $c = -1/4$) and the term π_{13} is written as $\pi_{13} = [(v_i)^{1/2}(\rho_t)^{1/4}(W_L)]/(EI)^{1/4}$. The second π term π_{14} is written as:

$$\pi_{14} = [(v_i)^a(\rho_t)^b(EI)^c](\alpha) \quad (A27)$$

and in dimensional form as:

$$[M^0L^0T^0] = [L^1T^{-1}]^a[M^1L^{-3}]^b[M^1L^3T^{-2}]^c[M^0L^0T^0] \quad (A28)$$

The corresponding values of the exponents are obtained as ($a = 0$, $b = 0$ and $c = 0$) and the term π_{14} is written as $\pi_{14} = \alpha$.

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