Determination of the High Strain Rate Behaviour of a CuCrZr Alloy Using an Electromagnetic Forming Bench Test

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Abstract

A novel electromagnetic forming (EMF) bench test has been developed to characterize the dynamic behaviour of metallic materials. This paper presents the specific case of a CuCrZr wrought alloy, detailing both the experimental approach and the inverse numerical methodology. The primary advantage of the proposed method lies in its ability to calibrate a dynamic material model, which is particularly relevant for forming applications involving thin specimens, with thicknesses as low as 0.6 mm. The well-known Johnson-Cook model is used without consideration of the thermal softening term. The calibration is validated within the strain rate range of $[1\text{-}4000]s^{-1}$. It is indeed shown that this method generates a broad variation of strain rates during the 300 µs test duration. The benefits from using a strain rate sensitive law as opposed to a quasi-static one are also demonstrated. Analysis of plastic strains and peak stresses further indicates that the EMF test is particularly well-suited for ductile materials, whereas brittle materials may fracture prematurely or fail to deform sufficiently. Limitations regarding the non-uniqueness of the calibrated model and the incorporation of thermal effects are briefly discussed.

Keywords

Dynamics, Modelling, Forming

1 Introduction

High Pulsed Power (HPP) processes involve the rapid discharge of stored electrical energy (typically in the range of tens of kJ) into a specialized setup. This energy is converted into magnetic pressure, which can be harnessed for various applications such as electromagnetic forming, welding, or crimping of metallic components. Regardless of the application, both the tooling and the workpiece experience severe mechanical loadings under dynamic conditions during an HPP process. High strain rates are particularly advantageous in metal forming of thin materials. It is therefore crucial to characterize the dynamic behaviour of materials to better predict the lifetime of tooling and the final shape of a workpiece.

Depending on the range of strain rates considered, different experimental technics are available to assess the dynamic behaviour of a metal such as the Split Hopkinson Pressure Bars test (10^2 to 10^4 s^{-1}) or the Taylor Test (10^4 to 10^6 s^{-1}). Novel technics are being developed as well, for instance the High Current High Strain Rate Tensile testing platform (10^3 to 10^4 s^{-1}) developed by Wu et al. (2024) to study a CuCrZr alloy.

This study presents an Electro-Magnetic Forming (EMF) bench test designed to calibrate materials models under bending driven and dynamic conditions for ductile metals with high electrical conductivity. The design is inspired by the approach outlined by Golovaschenko and Mamutov (2004), later adapted by Jeanson in her thesis (2016). The EMF bench test is more user-friendly than the Split Hopkinson Pressure Bars and can achieve strain rates around 10^3 s^{-1}, making it suitable for characterizing flat materials with thicknesses ranging from 0.6 mm to 3 mm. The experimental method is coupled with an inverse numerical method, which is a common routine when it comes to material models calibration (Meuwissen et al., 1998 ; Hernandez et al., 2013).

2 Experimental Procedures

The material used in the study is a wrought CuCrZr which properties are presented in the **Table 1**. The CuCrZr alloy is frequently used in the HPP field because of its good balance between electrical conductivity and mechanical strength.

Chemical composition (wt. %)						Density (g/cm³)	Hardness HB	Electrical Conductivity (m/Ω.mm²)
Cu	Cr	Zr	Fe	Si	Others			
Bal.	0.77	0.067	0.037	0.017	< 0.2	8,9	118-124	46.8-47.4

Table 1: *CuCrZr chemical composition and physical properties*

The ambient tensile behaviour of the material is investigated in quasi-static conditions. According to the ASTM E8 recommendations, a strain rate of 2.5x10^{-4} s^{-1} is employed and the specimen geometry is rectangular with a 50 mm gauge length and a 2 mm thickness.

The EMF bench test is presented **Fig. 1**. A dog bone specimen (thickness 2 mm, width 10mm) is held by clamps onto a coil with a polyimide film electrically insulating the specimen from the coil. The coil is designed with a slot so as the specimen acts as a short-

circuit. The underlying physical principle of the EMF bench test is depicted in the **Fig. 2.** When the electrical energy stored in a capacitor bank is discharged into the EMF set-up, which can be assimilated to an RLC system, the resulting electrical current flowing through the coil and the specimen generates a magnetic field. An electromagnetic force, known as Lorentz force, is consequently produced, deforming the specimen. The equivalent RLC parameters are specified in the Fig.1. The experiment being voltage-controlled, the voltages used in this study are 9 kV, 11 kV and 12 kV (*i.e.* respectively 3.24 kJ, 4.84 kJ and 5.76 kJ of discharged energy). A Rogowski coil measures the current at the coil terminals.
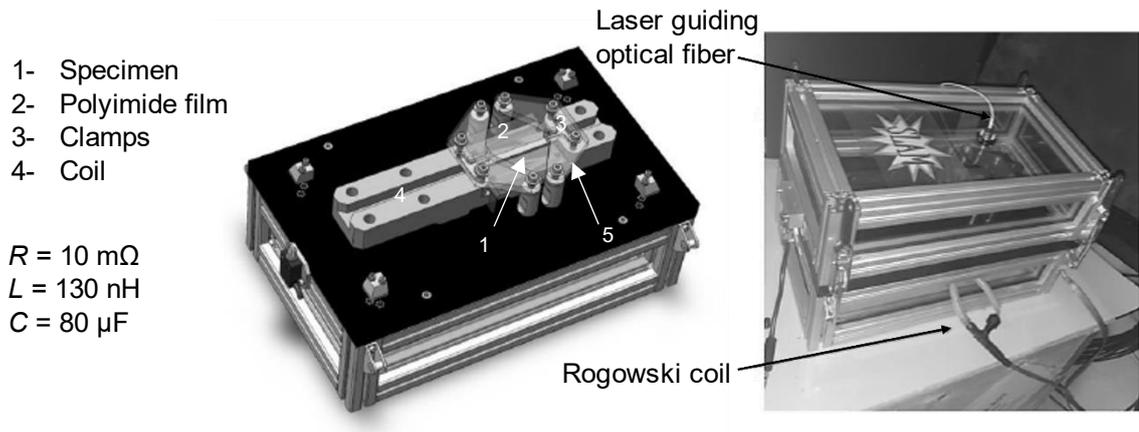
1- Specimen
2- Polyimide film
3- Clamps
4- Coil

R = 10 mΩ
L = 130 nH
C = 80 µF

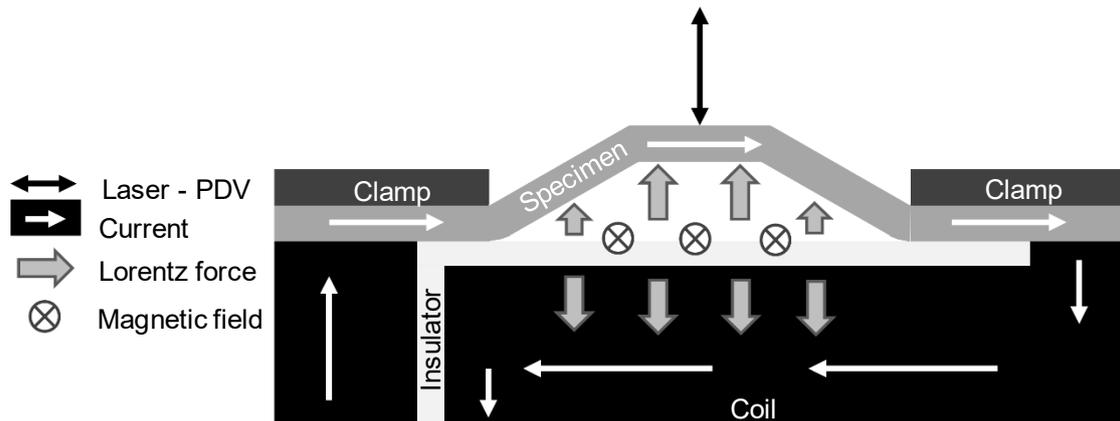**Figure 1**: *The Electro-Magnetic Forming bench test*

Figure 2: *The Electro-Magnetic Forming principle*

A Photon Doppler Velocimeter (PDV), with a laser focused on the central point (CP) of the upper gauge length of the specimen, measures the frequency shift of the laser before and after the interaction with the moving specimen. Raw data are processed using Python to calculate the main output which is the velocity of the CP as a function of time. The graph obtained can be divided into two phases:

1. A first phase with an increase of the velocity followed by a steady state. This phase corresponds to the inertial behaviour of the specimen, solely depending on the loading and the specimen characteristics (density, dimensions) ;

2. A second phase with a brief increase in the velocity value followed by a sharp decrease, both accounting for the material response due to the propagation of the plastic deformation at the CP.

The experiment is simulated using the LS-Dyna software with the corrected experimental current applied to model the loading conditions. Material law parameters are then calibrated thanks to an inverse method which compares the simulated and experimental CP velocity data. The mesh consists in five hexaedric elements through the thickness.

The **Fig. 3** proposes a summary of the general methodology developed in this study.
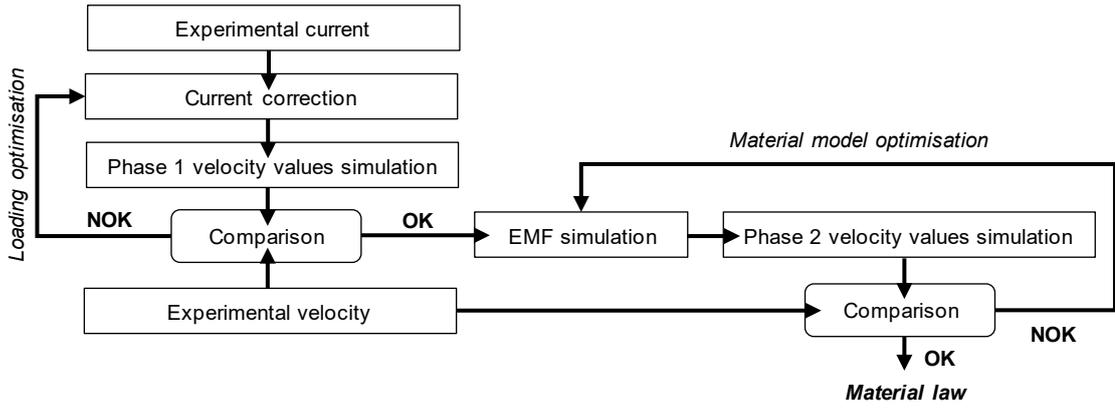

Figure 3: *Identification methodology of a dynamic material law using the EMF bench test and an inverse method via LS-Dyna (inspired from Jeanson (2016)). NOK = non-OK*

3 Results

3.1 Quasi-Static Tensile Behaviour

The **Fig. 4** shows the experimental results from the tensile tests. A Ludwik model is calibrated with a fairly good fitting. The general Ludwik material law is given by the **Eq. 1**.

$$\sigma = \sigma_0 + k \cdot \varepsilon_p{}^n \tag{1}$$

with σ the true stress, σ_0 the yield stress, ε_p the plastic strain, k and n materials constants being respectively the coefficient and the exponent of strain-hardening.

Identifying a Ludwik constitutive material law as a suitable model for the quasi-static behaviour is convenient since the Johnson-Cook (JC) model, one of the most commonly used dynamic laws, builds upon it. As expressed in **Eq. 2**, it is a multiplicative model that incorporates the strain rate sensitivity and the thermal softening through two factors applied to the Ludwik quasi-static model (Johnson and Cook (1983)).

$$\sigma = (\sigma_0 + k \cdot \varepsilon_p{}^n)(1 + C \cdot ln\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}})(1 - (\frac{T - T_r}{T_m - T_r})^m) \tag{2}$$

with $\dot{\varepsilon}$ the strain rate, $\dot{\varepsilon}_0$ the strain rate at reference state taken as 1 s^{-1}, T the temperature, T_r the room temperature, T_m the melting temperature, C and m material constants being respectively the strain-rate hardening coefficient and the thermal softening exponent.
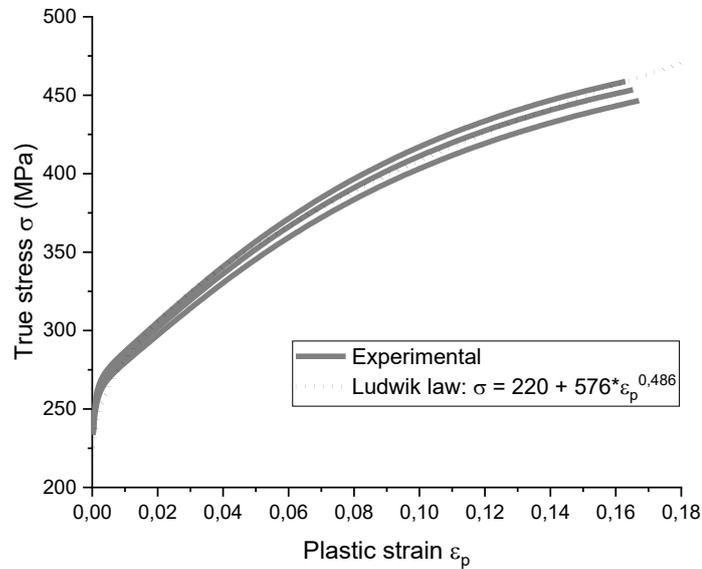

Figure 4: *Quasi-static tensile behaviour at ambient temperature of the CuCrZr alloy and identification of the Ludwik model parameters*

3.2 Dynamic Testing

The **Fig. 5a** shows the EMF results along with clarifications regarding the different phases of the specimen behaviour during the experiment. The maximal current values measured for each condition are also specified. The **Fig. 5b** illustrates the specimen shape during the different stages of the EMF.
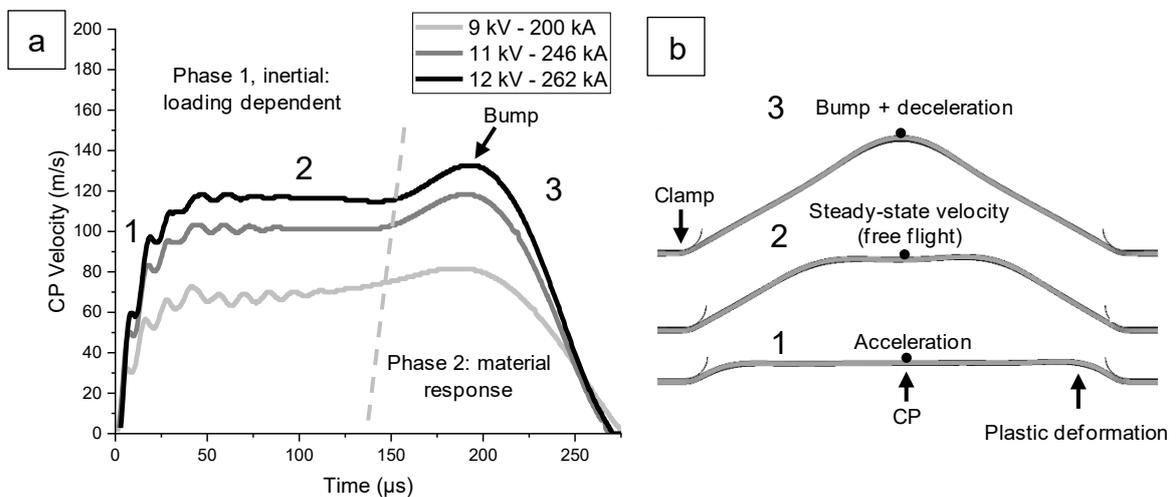

Figure 5: *a. CP velocities results after EMF tests. Dashed line separate "phase 1" from "phase 2" ; b. Specimen deformation with regards to the 3 stages of the EMF (LS-Dyna)*

3.3 Material Model Calibration

The JC model calibrations are presented **Fig. 6**. The thermal softening is not activated (m = 0). The JC parameter C is first calibrated at 12 kV and then tested at 9 kV and 11 kV. A good fitting between experimental and simulated data is obtained, leading to a C value of 0.01 suitable to describe the CuCrZr behaviour during an EMF test. A comparison of the CP velocity calculated when C = 0, *i.e.* when no strain-rate sensitivity is considered, proves that the Ludwik law from the Fig. 4 is insufficient to describe the material behaviour.
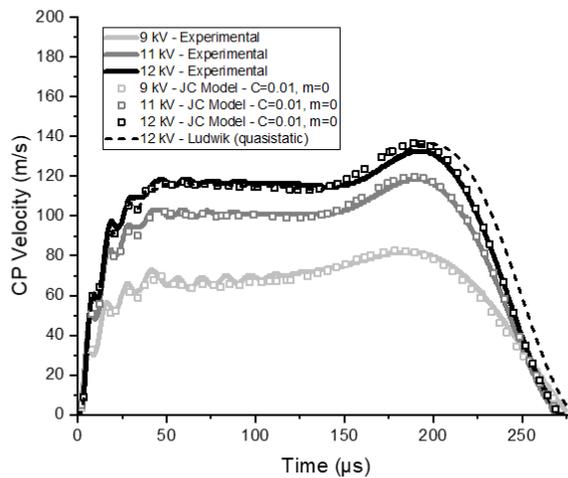

Figure 6: *JC model calibration (LS-Dyna) with no thermal softening and comparison with the EMF simulated curve obtained with a Ludwik quasi-static law*

Note that this work does not address the non-uniqueness of the calibrated law. Although calibration at three different voltage levels significantly narrows down the range of possible solutions, multiple combinations of JC parameters may still yield an acceptable fit to the EMF data. To address this issue, additional criteria need to be implemented. Ongoing work is also exploring alternative material models, such as the Cowper-Symonds law. Furthermore, the calibration process becomes even more complex when $m > 0$ is considered, as thermal effects arising from plastic strains and the Joule effect -each varying spatially within the specimen- must be accounted for.

3.4 Stress and Strain States

Once a material model is identified, it is possible to analyse the stress and strain states within the specimen during an EMF test. The **Fig. 7** shows the map of the maximum Von Mises stresses reached during a 12 kV test while the **Fig. 8** presents the distribution of plastic strains at the end of the same test. The areas of maximal stresses and plastic strains are located beneath the clamps. Special care must be given to prevent any necking in this area as it would compromise the validity of the experiment. Outside of this critical area, the stress and plastic strain fields are largely homogeneous across the specimen. A slight gradient is observed near

the CP where the bottom face experiences lower stresses and strains. Both results from Fig. 7 and 8 suggest that the EMF bench test is well-suited for characterizing ductile materials whereas brittle materials would likely break prematurely.
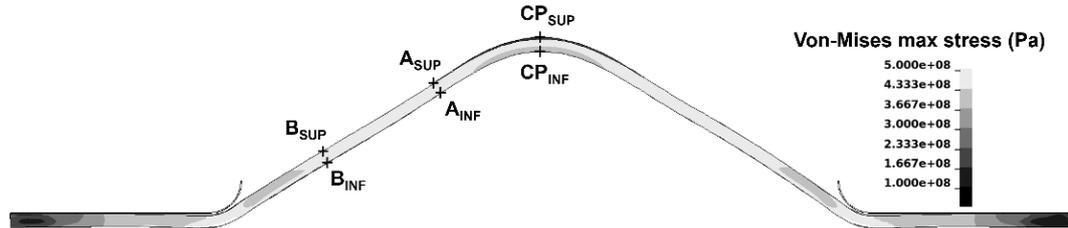

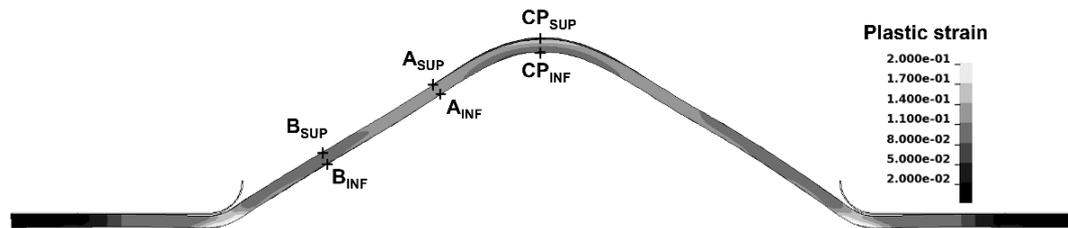*Figure 7: Maximum Von-Mises stresses during a 12 kV EMF test*

Figure 8: Effective plastic strain after a 12 kV EMF test

The **Fig. 9** shows the variation of strain rates during a 12 kV test. Six positions are analysed as indicated in the Fig. 7 and 8. Due to the propagation of the plastic deformation toward the CP, both the timing and magnitude of peak strain rates depend on the position along the length and the thickness of the sample. The top face undergoes higher strain rates, ranging from 1500 s^{-1} up to 4000 s^{-1} while the bottom face sees lower rates, between 500 s^{-1} and 1500 s^{-1}.
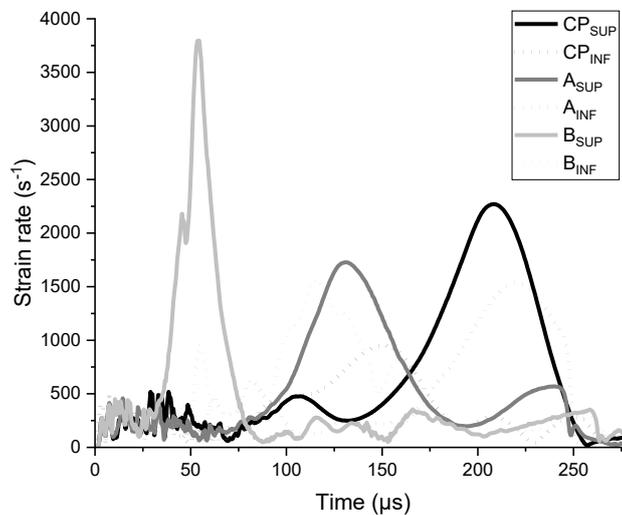

Figure 9: Strain rates variation along the specimen and during a 12 kV EMF test

A key takeaway here is that an EMF test performed at a fixed voltage does not result in a constant strain rate loading but rather in a wide range of strain rate values. Consequently, the material model identified in the previous section should be regarded as an apparent law valid within the [1-4000] s^{-1} strain rate range.

4   Conclusions

An experimental method based on electro-magnetic forming has been developed to characterize the dynamic behavior of ductile metallic materials with good electrical conductivity. The calibrated material model is validated within the strain rate range of $[1-4000]$ s^{-1}. The specific case of the CuCrZr is studied demonstrating the clear benefits from using strain-rate sensitive laws over quasi-static models. Further efforts are required to reduce the number of plausible solutions obtained via inverse identification and to incorporate the thermal effects arising from plastic deformation and the Joule effect.

Acknowledgments

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