# An automatic system of handling and heating samples during dynamic hot compression tests

G. Soardi[1,a], C. Guerra[1,b], M. Seiti[1,c], A. Abeni[1,d*], A. Attanasio[1,e], E. Ceretti[1,f]

[1]Department of Mechanical and Industrial Engineering, Università degli Studi di Brescia, Via Branze 38, Brescia, 25123, Italy

[a]giuseppe.soardi@unibs.it, [b]costantino.guerra@unibs.it, [c]miriam.seiti@unibs.it, [d]andrea.abeni@unibs.it, [e]aldo.attanasio@unibs.it, [f]elisabetta.ceretti@unibs.it

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**Abstract.** The study describes an innovative system to minimize the effect of thermal gradient in hot compression tests for alloy characterization. The mechanism separates the sample from the tool by using a pneumatic handle with refractory terminals and heats the samples through induction. Once a uniform temperature distribution is achieved, the samples are positioned on the lower punch, and the compressions are performed. Tests on stainless steel validated the efficacy, enabling calibration of Hansel-Spittel constitutive model using Particle Swarm Optimization. Results demonstrate that the innovative system and the data elaboration algorithm improves the precision of flow stress, under several temperatures and strain rates up to 20 $s^{-1}$. This method can be employed to achieve material calibration, useful for the virtual simulation of the processes with Finite Element Method. This approach offers a robust, cost-effective alternative for material testing in hot plastic deformation processes.

## Introduction

The Finite Element Method (FEM) is widely employed to simulate metal hot-forming operations, including rolling, forging, and extrusion. The accuracy of numerical simulations is significantly influenced by input factors such as friction conditions, contact modelling, and material characterization [1]. Flow stress models are crucial for precisely characterising material behaviour under different strain, temperature, and strain rate [2,3].

Experimental methods, such as isothermal hot compression tests, are commonly employed to build constitutive models. These models can be obtained with three methodologies: i) physically-based, which consider metallurgical mechanisms and require extensive calibration settings; ii) artificial neural networks (ANNs), which exploits machine learning algorithm for predictions without predefined equations; iii) phenomenological models, such as Hansel-Spittel, Johnson-Cook, and Arrhenius, which offer a balance between computational efficiency and accuracy, making them widely used in high-temperature forming simulations [4,5].

Independent from the methodology selected, the material behaviour at increased temperatures and high strain rates is significantly influenced by dynamic strain hardening. According to the strain rate specifications, different experimental systems can be selected. Servo-hydraulic presses are often employed for strain rates up to 10 $s^{-1}$, while strain rates higher than 1000 $s^{-1}$ usually require Split Hopkinson Pressure Bar (SHPB) [6]. Although successful, compression tests frequently encounter temperature gradients due to heat transfer and friction, which compromise the precision of flows stress characterization [7].

Therefore, this study introduces a novel, automated, controlled method for sample handling and heating, aimed at ensuring constant temperature distribution during hot compression experiments. The technology is validated through experiments on AISI 304 stainless steel, chosen due to the challenges of electromagnetic induction heating, which causes thermal gradients at the contact surface. Experimental data are used to calibrate Hansel-Spittel model through Particle Swarm

Optimisation. Once the model is calibrated on the experimental data, it can be easily implemented in commercial FEM software to simulate hot plastic deformation processes involving the material.

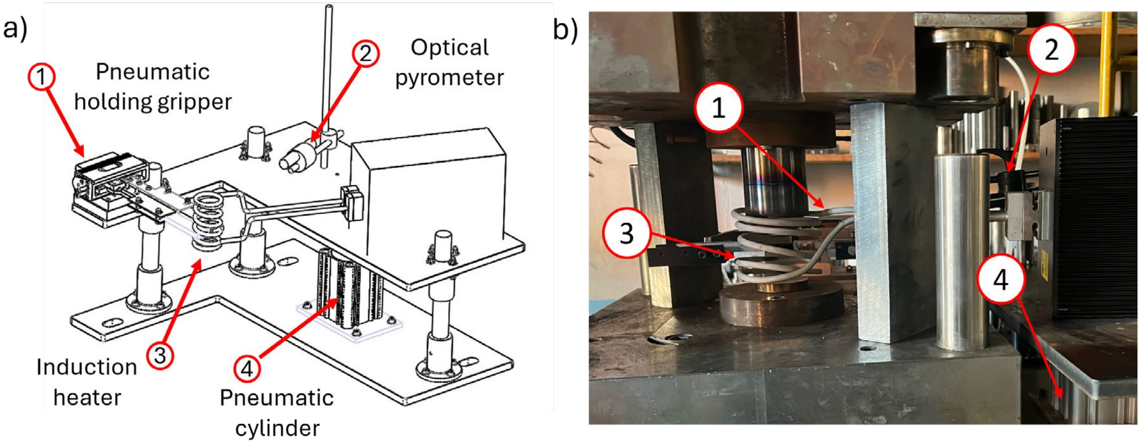

***Fig. 1**. Representative (a) technical drawing and (b) figure of the developed system.*

## Materials and Methods

This section describes the methodology used to characterize AISI 304 through the proposed high-speed hot compression test system. The samples were prepared by cutting a Ø10 mm bar, achieving cylinders with the same diameter and a height equal to 30 mm. A 100-ton hydraulic press was employed, equipped with four loadcells (Gefran CM K30M) and a linear potentiometer to measure the upper die displacement. A data acquisition system recorded signals with a sampling rate of 2 kHz. An induction heater with a feedback-controlled optical pyrometer was used to ensure rapid and contact-free sample heating. To minimize thermal gradients, an automated sample-handling system was then developed. This innovative system, visible in Fig. 1, featuring a pneumatic gripper and lifting mechanism, prevents heat conduction between the specimen and the lower plate, ensuring homogeneous heating. The functioning can be summarized as follows:

1. The cold sample is positioned on the lower punch, the holding gripper is open, and the pneumatic cylinder is lowered
2. The holding gripper is closed, and the sample is grabbed with the terminals built in a cement-based material with low conductivity and invisible to the magnetic field.
3. The pneumatic cylinder lifts the plate with the gripper, the induction heater and the pyrometer, raising the sample from the lower punch (no contact).
4. The induction system heats the sample to the target temperature with the feedback control of the pyrometer.
5. Once the temperature is achieved, the pneumatic cylinder lowers the plate, and the sample returns in contact with the lower punch.
6. Immediately after, the holding gripper is open with a distance higher than the upper punch diameter, which descends, and the compression occurs.

A full factorial $3^2$ experimental plan was performed by testing three temperatures (900, 1050, and 1200 °C) and three compression speeds which were selected in order to obtain the following average strain rates of: 2.4, 7.2 and 15.8 $s^{-1}$. The selected temperatures and strain rates represent typical values employed in hot plastic deformation processing of AISI 304, especially in forging and hot rolling. Each test was repeated three times to statistically validate the procedure for a total amount of 27 compression tests.

The Hansel-Spittel constitutive model (as depicted in Eq. 1) was calibrated by using the Particle Swarm Optimization (PSO) stochastic algorithm. A population of 100 particles and 2000 iterations was employed to find the optimized set of Hansel-Spittel constants. The lower limits of the model coefficients were set to -1, while the upper limits of coefficient A was set to 10000 while the coefficients $m_1$, $m_2$, $m_3$, $m_4$ were set to 1.

$$\sigma(\varepsilon,\dot{\varepsilon},T) = Ae^{m_1T}\varepsilon^{m_2}\dot{\varepsilon}^{m_3}e^{\frac{m_4}{\varepsilon}} \qquad \text{Eq. (1)}$$

## Results

Fig. 2 shows a morphological comparison between a sample heated in contact with the lower plate and a sample heated with the proposed system. In Fig. 2(a) is visible as the thermal gradient affected material deformation, while in Fig. 2(b) the shape of the compressed sample is uniform as a consequence of a constant temperature distribution. The experimental stress-strain values were fitted in the Hansel-Spittel model, and the optimized coefficients determined with PSO algorithm are visible in Table 1.

***Table 1.*** *Optimized coefficients of the Hansel-Spittel model.*

| A | $m_1$ | $m_2$ | $m_3$ | $m_4$ |
|---|---|---|---|---|
| 10838 | -0.00409 | -0.257 | 0.161 | -0.107 |

(a) (b)

***Fig. 2.*** *Samples compressed, without using the manipulation system (a) and with the system (b).*

Fig. 3 offers an example of the computed stress versus strain for T = 900°C. Analogue charts were obtained for the other temperatures. The complete dataset was subsequently used to fit the Hansel-Spittel model.

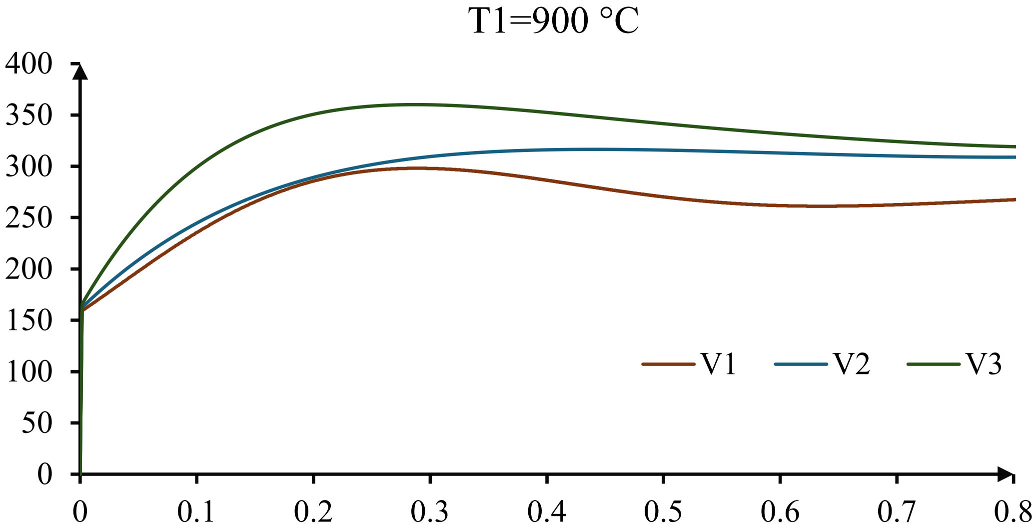

***Fig. 3.*** *Flow stress data for T = 900°C with three different compression speeds.*

Fig. 4 shows the calibrated Hansel-Spittel model, which demonstrates accurate predictions for maximum stress. The flow stress increases up to a plastic strain of 0.3 and subsequently it slightly decreases. The strain rate influence decreases at higher temperatures. Particularly high temperatures significantly soften the material, whereas strain rate variations have a limited effect.

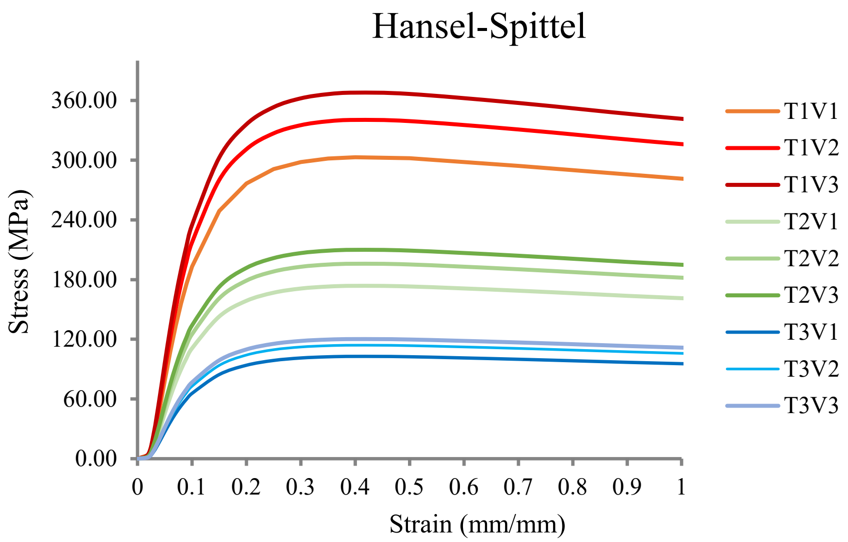

***Fig. 4.*** *Calibrated flow stress model at T=900 °C, T=1050 °C and T=1200°C, by changing the strain rates.*

## Preliminary Conclusion

This work presents the development of an innovative pneumatic handling system designed to enhance the reliability of high-speed hot compression tests, particularly for metallic alloys such as AISI 304 stainless steel. The system addresses the issue of thermal gradients induced by the contact between the sample and the dies during the heating phase. By avoiding contact during the heating phase until the target temperature is reached, the proposed solution ensures improved thermal homogeneity, increasing the accuracy of the mechanical characterization. Hansel-Spittel constitutive model was calibrated employing a Particle Swarm Optimization algorithm, achieving findings which confirm that the proposed model effectively captures the material response under varying thermal and strain rate conditions. The resulting model can be added to commercial Finite Element software to simulate thermo-mechanical processes considering the actual properties of the workpiece material. Despite being a work in progress, the proposed methodology aims to develop a cost-effective alternative to commercial testing machines, as it can be integrated with existing industrial hydraulic or mechanical presses.

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