

IMPROVING FEM ACCURACY IN HOT FORGING SIMULATIONS THROUGH HYDRAULIC PRESS POWER LIMIT CURVE CHARACTERISATION

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Abstract

Finite Element Method (FEM) simulations are essential for predicting feasibility, outcomes, and defects in hot plastic deformation processes. In small batches or single-component production, a reliable model is crucial to minimise the number of physical trials, material waste, and overall time and energy consumption. However, achieving high simulation accuracy depends on defining precise boundary conditions, particularly regarding material properties and specific process parameters.

In hydraulic press forging, a primary challenge involves defining an objective relationship for the downstroke speed, as it strongly influences both the workpiece's mechanical response and the total operation time.

This study presents a methodology to identify the Power Limit (PL) curve of a hydraulic press by correlating the maximum downstroke speed with the applicable forging forces in an industrial context. An extensive dataset, derived from real-world forging operations performed on blanks of different geometries and materials, was processed to construct the curve. The proposed model was validated by comparing FEM results with industrial experimental data, demonstrating high reliability. In addition, the study shows that this approach can be tailored to characterise the most representative forging conditions in terms of forging downstroke speed for specific materials, leading to the definition of a Material Operating Characteristic Curve (MOCC). The model offers a robust framework for enhancing the predictive capability of FEM simulations for hot forging processes.

Keywords: FEM simulations, forging, hydraulic press, power limit curve

1. INTRODUCTION

Nowadays, the widespread adoption of FEM simulations has become essential for supporting the design of hot forming processes. The inherent complexity of these operations, coupled with the microstructural phenomena experienced by a component during hot plastic deformation, can lead to computationally intensive and challenging simulations. For this reason, research focused on defining accurate boundary conditions is crucial for obtaining reliable results [1,2], which are fundamental in identifying potential issues in manufacturing process design. For instance, Venet et al. developed an experimental–numerical approach to identify the constitutive laws of 42CrMo4 steel [3], achieving a robust description of material behaviour under large deformation conditions. Similarly, Wu et al. investigated the effect of varying initial ingot temperatures, introducing the concept of “ultra-high temperature forging” through simulation-based analysis [4].

Among the various research areas in FEM-based forging modelling, the press downstroke speed is a key parameter governing the workpiece response [5]. In the metal forming industry, hydraulic presses are widely used due to their robustness and reliability, leveraging fluid power to generate motion and managing heavy loads within a relatively compact actuator configuration [6]. In hydraulic presses, speed kinematics can be controlled in terms of power, particularly by a Power Limit (PL) curve [7]. This curve defines the maximum achievable downstroke speed for any given force up to the press's nominal capacity. As illustrated in **Figure**

1 - a, the PL curve represents the boundary of the press operating conditions in terms of force and downstroke speed, thereby defining the feasible operating region. Conditions outside this region are unattainable by the hydraulic system. During forging, the initial downstroke speed is typically set by process engineers and corresponds to the maximum deformation speed (MaxS) imposed throughout the entire process. This value ranges from zero to the maximum no-load speed of the press. In an ideal forging operation (**Figure 1 - b**) - assuming no operator-induced slowdown - MaxS (point A) is maintained until the power demand exceeds the press's nominal capacity (segment A–B), while the force increases with the deformation load. Once the required power reaches the available maximum (point B), the system self-regulates by reducing the downstroke speed along the PL curve (segment B–C). Upon reaching the target stroke (point C), the velocity drops abruptly to zero (segment C–D). In real processes (**Figure 1 - c**), however, this deceleration is more gradual; operators typically begin the slowdown before reaching the target stroke (point D), resulting in operation below the PL curve (segment C–D).

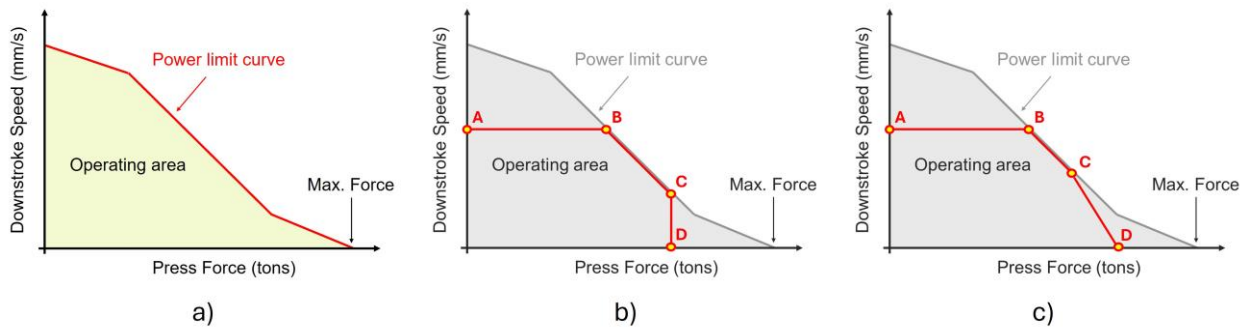


Figure 1 Schematic representation of hydraulic press kinematics: a) PL curve defining the operating area; b) theoretical downstroke speed regulation during an ideal forging operation; c) observed downstroke speed evolution in a real forging process

In this study, industrial data from a hydraulic press were analysed to identify a PL curve that accurately characterises the system, ensuring a reliable model for predicting press kinematics during metal forming processes. The dataset comprises many forging operations performed on three alloys: 42CrMo4 steel, Ti-6Al-4V, and IN718. In addition, these data were used to develop a Material Operating Characteristic Curve (MOCC) for each alloy. Derived from the statistical analysis of actual industrial operations, the MOCC represents the most probable working conditions - defined by downstroke speed and press force - for each material, aimed at enhancing simulation accuracy. Finally, the PL curve and the MOCCs were implemented as input parameters in simulations of three separate forging operations, one for each material. The comparison between numerical and experimental results validated the effectiveness and reliability of the proposed curves.

2. MATERIALS AND METHODS

The industrial facility considered in this work features a hydraulic press used for hot forging of metal blanks. The plant is equipped with an acquisition system that records all the most important operational parameters, including the downstroke speed, the press force, and the stroke. All process data is recorded and stored in a dedicated archive. For this research, more than 100 forming processes performed on 42CrMo4 steel, Ti-6Al-4V alloy, and IN718 alloy were analysed, totalling approximately 90,000 force-speed data pairs.

To construct the PL curve, the full range of forces applied by the press (from zero to the maximum applicable load) was discretised into 25 intervals. From the industrial dataset, all force-speed data pairs were grouped according to the interval to which the force value of each pair belonged. The PL curve was then constructed by pairing the maximum recorded velocity within each interval with the corresponding mean force value. To complete the curve, two additional pairs were included: an initial pair (zero force, with velocity equal to that

assumed for the first interval), and a final pair (maximum press load, with zero velocity). A graphical representation of this construction of the PL curve is reported in **Figure 2**. The development of the MOCC represents an evolution of the PL curve methodology. Each material was considered individually, resulting in three distinct MOCCs. The operating range of downstroke speeds was discretised into 10 intervals, effectively partitioning the force-speed domain into a 25x10 cells. The frequency of data pairs falling within each cell was then calculated. The MOCC was derived by considering, for each force interval, the mean velocity of the most populated cell. Consequently, the resulting curve serves as an empirical approximation of a conditional-mode-based relationship [8]. Consistent with the PL curve construction, two additional pairs were added to finalise the MOCC. A schematic representation of the method to construct the MOCC is proposed in **Figure 3**.

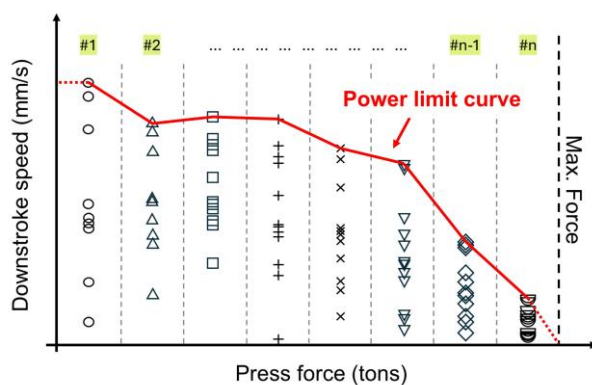


Figure 2 Schematic representation of the data-based characterisation of the PL curve

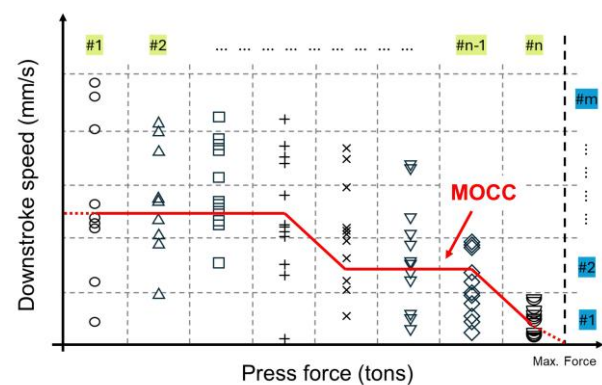


Figure 3 Schematic representation of the data-based characterisation of the MOCC

Once the curves were obtained, an upsetting operation was experimentally performed for each material considered in the study. These forming processes were carried out under typical industrial conditions, ensuring the collection of representative results that faithfully reflect standard production practice. **Table 1** summarises the key parameters of the three forming processes conducted on the respective blanks. Each upsetting operation was then simulated twice. In the first simulation, the PL curve was used to characterise the press kinematics, whereas in the second one, the MOCC was applied to the material being processed. All simulations were carried out using the commercial software DEFORM (Scientific Forming Technologies Corporation, Columbus, USA). The remaining boundary conditions were defined based on prior experimental experience and relevant literature [9–11]. Finally, the force–time curves obtained from the simulations were compared with the experimental industrial data to evaluate the robustness and reliability of the proposed methodology.

Table 1 Main characteristics of the simulated hot forging processes for the three materials

Material	Blank initial diameter (mm)	Blank initial height (mm)	Blank final height (mm)
42CrMo4	530	614	211
Ti-6Al-4V	120	175	125
IN718	240	200	135

3. RESULTS AND DISCUSSION

As a result of the data-driven analysis performed on the available dataset, **Figure 4** presents the normalised PL curve of the investigated plant. The curve exhibits a monotonically decreasing trend, with the maximum

downstroke speed decreasing as the requested force increases. Additionally, the curve shows a marked decline starting at approximately 65 % of the maximum force, while remaining relatively constant below this threshold.

Figure 5 displays the normalised MOCCs for each alloy considered in the study. Normalisation along the x-axis was achieved by scaling the force values by the plant's maximum load, while the y-axis was normalised by dividing the downstroke speeds by the maximum velocity defined by the PL curve. Since the MOCCs represent the operating conditions of each specific alloy, it is evident that all materials are generally processed within the feasibility operating region below the PL curve, as previously defined in **Figure 1**. Furthermore, the MOCCs differ significantly among the considered alloys. While the 42CrMo4 steel is typically processed at higher velocities, the IN718 and Ti-6Al-4V alloys operate under more conservative conditions. This discrepancy is attributed to the specific metallurgical needs of these alloys, which demand lower strain rates to prevent forging defects and ensure microstructural integrity.

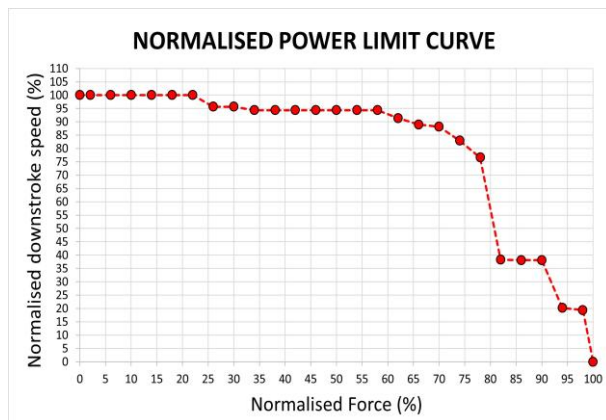


Figure 4 Normalised PL curve

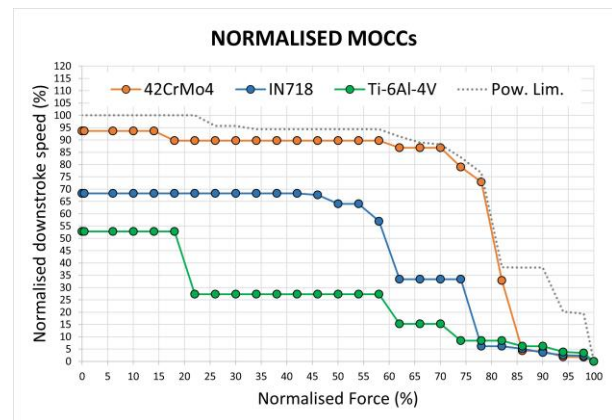


Figure 5 Normalised MOCCs

Once the upsetting tests were performed, the measured press forces (black lines in **Figure 6**) were compared with the numerical results (red lines in **Figure 6** for PL-based simulations, and dotted lines for MOCCs-based simulations). The results were interpreted in relation to the primary objective of the simulation: assessing process feasibility. Specific emphasis was placed on the maximum forging force to determine whether the plant capacity was sufficient for the operation. As illustrated in the graphs, the predicted maximum forces for 42CrMo4 steel (**Figure 6 - a**), IN718 alloy (**Figure 6 - b**), and Ti-6Al-4V alloy (**Figure 6 - c**) exhibit a strong correlation with experimental data. Notably, the maximum force predicted by the PL-based simulations is consistently higher than that predicted by the MOCC-based simulations. This discrepancy arises because the PL curve exhibits a higher downstroke speed - and therefore higher strain rates - than those of the MOCC curve, leading to a more pronounced material flow stress response. For the 42CrMo4 steel, the experimental maximum load aligns closely with that predicted by the MOCC-based simulations, confirming that the forming process was conducted under highly representative working conditions, i.e., the objective of the MOCC methodology. For the IN718 and Ti-6Al-4V alloys, the experimental maximum loads are very close - within a few percentage points - to the values predicted by both the PL-based and MOCC-based simulations, indicating the robustness of both models in these instances. Overall, the proposed method is highly reliable for assessing process feasibility. While the PL-based approach represents extreme working conditions - limiting the downstroke speed based on the maximum available power of the press - the MOCC-based approach is more conservative, as demonstrated in **Figure 5**. It is recommended to employ both modelling strategies to better understand the range of conditions under which the forging process may occur.

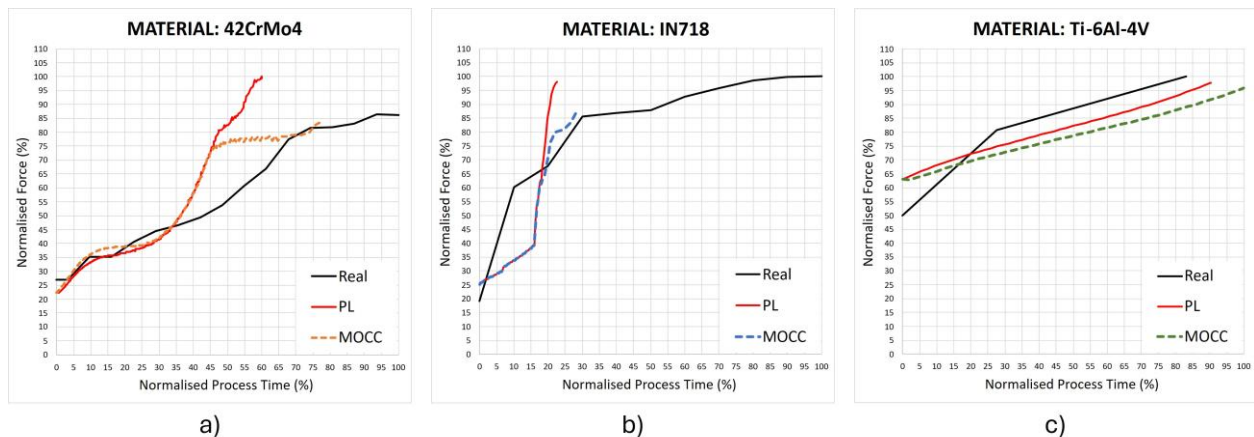


Figure 6 Comparison between experimental press force and simulated results using PL and MOCC kinematics for: a) 42CrMo4, b) IN718, and c) Ti-6Al-4V alloys

4. CONCLUSIONS

The study proposes a robust framework for characterising hydraulic press kinematics to enhance the predictive accuracy of FEM simulations in hot forging. Analysis of an extensive historical dataset from an industrial plant enabled the successful establishment of the Power Limit (PL) curve of the press. Moreover, Material Operating Characteristic Curves (MOCCs) were developed for 42CrMo4 steel, Ti-6Al-4V, and IN718 alloys, representing the most probable operating conditions employed by operators in industrial practice for each material. The comparison between simulated upsetting tests and experimental data demonstrated high reliability in assessing process feasibility, indicating a strong correlation between predicted and actual maximum forces required for forming operations. While PL-based simulations accurately depict extreme working conditions up to the plant's maximum capacity, the MOCC-based approach provides a more realistic and representative prediction of real-world processing scenarios. In conclusion, the integrated use of both simulation approaches is recommended to achieve a comprehensive understanding of feasible operational conditions. Adopting this dual-modelling approach can significantly minimise the necessity for physical trials, reduce material waste, and optimise energy consumption in large-scale industrial forging operations.

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