Optimization of Geometry and Process Parameters in Multi-Directional Forging (MDF)

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***Abstract*—Multi-Directional Forging (MDF) is one of the promising Severe Plastic Deformation (SPD) method for producing bulk ultrafine-grained alloys However, its industrial application remains limited, mainly because the mechanical gains achieved are often insufficient relative to the energy and load required. This study aims to address this limitation by quantifying and optimizing the effects of three key processing parameters of MDF: initial workpiece geometry, deformation temperature and, single-pass reduction ratio. The initial workpiece geometry parameter was selected as (10x10x10mm), (10x10x20mm), and (10x10x40mm). And, the deformation temperatures were set at 20 °C, 100 °C, and 200 °C to represent cold, warm, and low-hot forging conditions. Besides, single-pass height reductions of 5%, 10%, and 20% were also chosen. Using the three defined parameters, a 3^3 full-factorial design was initially considered, which would normally require 27 simulations. However, by applying the Taguchi design of experiments (DOE) method, the number of required simulations was effectively reduced to just 9. However, by employing the Taguchi design of experiments (DOE) method, the number of required simulations was effectively reduced to just 9.**

All parameters not included in the FEA matrix were kept constant throughout the simulations. For each processing scenario, effective strain values were recorded, as effective strain is a key indicator directly correlated with improvements in mechanical properties. To identify the optimal set of process parameters, a Taguchi optimization approach was employed. This method, based on orthogonal arrays, efficiently explores multi-factor design spaces and was used here with the specific aim of maximizing the effective strain. The resulting parameter combination represents the most favorable condition for enhancing plastic deformation through the MDF process.

This study demonstrates that the MDF process, when optimized using a Taguchi design, can achieve an effective strain value greater than 1.8 mm/mm under the optimal parameter combination of 10×10×10 mm billet size, 20 °C forming temperature, and 20% height reduction. These results indicate that substantial plastic deformation can be obtained with relatively low forming complexity and lower thermal input. While the strain levels remain slightly below those of conventional SPD methods like ECAP, the process benefits from lower energy demands and the elimination of complex die requirements. The findings highlight MDF's potential as a practical and scalable SPD alternative for high-performance aluminum alloys, offering a data-supported route toward energy-efficient bulk nanostructuring and forging process design.

***Keywords*— Finite Element Analysis (FEA), Multi-Directional Forging (MDF), Severe Plastic Deformation (SPD), Taguchi Optimization.**

I. Introduction

Severe Plastic Deformation (SPD) is a family of metal‑forming techniques in which very large plastic strains, often above true strains of 3, are imposed on bulk billets without altering the overall dimensions of the workpiece. The key objective is to obtain ultrafine‑grained (UFG) or nanostructured microstructures that markedly increase strength through Hall-Petch grain‑boundary strengthening [1–4] . Since the inspiring works on Equal‑ Channel Angular Pressing (ECAP) in the 1990s [5] and the subsequent demonstrations of high‑ pressure torsion [6, 7], accumulative roll bonding [8] and twist extrusion (TE) [9–11] etc., extensive research has shown that SPD can reduce grain size below 1 to 3 µm and more than double the yield strength while retaining reasonable ductility in aluminum alloys such as AA6082 [12, 13].

Despite these advantages, conventional SPD routes remain difficult to industrialize. Most methods require multiple passes, specialized dies that experience severe wear and high press loads. And, because of the high dislocation density generated inter‑ pass or post‑ process heat treatments to restore ductility, all of which increase cost and cycle time [14–22]. Moreover, techniques like high‑ pressure torsion are restricted to small disk geometries [7], whereas ECAP is limited by channel size, making large‑ scale production challenging. Consequently, the uptake of SPD in industry has been modest.

Multi‑ directional forging (MDF), also called multi‑ axial forging, has emerged as a practical alternative that still falls inside the SPD definition because the billet is repeatedly compressed along orthogonal axes, accumulating high strain without significant shape change [23–26]. MDF requires only flat dies on a conventional hydraulic press, rendering the tooling far simpler than ECAP or TE and allowing processing of larger work‑ pieces. Finite‑ element analyses (FEA) have shown that successive 90° rotations promote a near‑ uniform effective strain and avoid corner folding provided that die friction and pass strain are properly selected [24, 26]. Nevertheless, the grain sizes achieved by MDF are typically in the sub‑ micron, rather than nanometre, range and therefore the strength increment is somewhat lower than in ECAP or TE for

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an equivalent total strain.

AA6082 is a medium‑strength Al‑Mg‑Si alloy widely used in transportation structures because of its good corrosion resistance and weldability. Recent studies confirm that ECAP, TE and MDF can all refine the grains of AA6082 [13, 14]. The choice between these routes, however, hinges on cost and scalability. MDF appears attractive because billet size is not strongly restricted, forging presses are global in industry and cycle times can be shortened by forging at moderately elevated temperatures to lower flow stress.

To design an efficient MDF schedule for AA6082, a number of parameters must be optimized, including forging temperature, strain per pass, and the sample dimensions. Taguchi design‑of‑experiments (DOE) methods has proved effective for identifying the most influential factors in SPD processes using only a limited set of simulations or trials [27–29]. FEA coupled with Taguchi DOE has recently been applied to optimize MDF of AA7xxx and AA2xxx series alloys, revealing that friction and per‑pass strain are the dominant variables controlling strain homogeneity and damage accumulation. Following this approach, the present study employs DEFORM‑3D simulations of MDF for AA6082 and a Taguchi optimization framework to propose a forging schedule that balances strain homogeneity with process efficiency. Based on the effective strain values obtained through DEFORM‑3D, the Taguchi method was applied to identify the optimal experimental combination that maximizes strain accumulation.

Accordingly, the aim of this study is to apply the multi-directional forging (MDF) method to AA6082 alloy under varying processing conditions and parameters, to evaluate the resulting effective strain values, and to determine the optimal combination using the Taguchi method for maximizing strain accumulation. In doing so, the study seeks to contribute to the literature by identifying the conditions under which the MDF process can be utilized more efficiently for this alloy.

II. Materials and Methods

In this study, a Finite Element Analysis-based approach was adopted to simulate Multi-Directional Forging (MDF) of AA6082 aluminum alloy using DEFORM-3D software. To reduce the number of required simulations and ensure statistically robust conclusions, the Taguchi design of experiments (DOE) method was employed.

Three key process parameters were selected based on relevant literature: *billet geometry, forming temperature, and height reduction per forging pass*. The billet geometries considered were 10×10×10 mm, 10×10×20 mm, and 10×10×40 mm, representing increasing aspect ratios. Forming temperatures were set at 20 °C (room temperature), 100 °C, and 200 °C to account for cold and warm forging conditions. Height reduction ratios per pass were defined as 5%, 10%, and 20% to vary the severity of deformation. These three parameters, each at three levels, form a full-factorial 3^3 design that would normally require 27 simulation runs.

However, by applying the Taguchi L9 orthogonal array, the number of simulations was reduced to 9 representative combinations. For each selected combination, a 3D model was constructed and simulated in DEFORM-3D under quasi-static loading conditions, assuming rigid dies, frictional contact, and isotropic material properties for AA6082. The boundary conditions and simulation inputs held constant across all combinations are listed in Table I. The simulations yielded the effective strain (ε_eff) values for each parameter set, which were used as the response variable in the optimization process.

TABLE I: Deform 3D Parameters

Process Type:	Cold Forming
Shape Complexity:	Moderate
Number of mesh:	20000 tetrahedral elements
Punch Speed:	1 mm/sec
Friction coefficient:	0,4

In all simulations, the MDF process was modeled as a single-pass operation. The pressing directions applied during a single MDF pass are schematically illustrated in Fig. 1 [26]. Each forging pass involved a uniaxial compression along a specific direction, and for consistency, all deformation was applied in only one pass. However, to realistically represent the deformation process in Deform‑3D and to obtain a stable and measurable effective strain (ε_eff), each operation was implemented as a sequence of three incremental operations within the simulation environment. The final effective strain value obtained at the end of the third operation was considered the representative outcome of a single MDF pass and used as the response variable in the Taguchi optimization analysis.

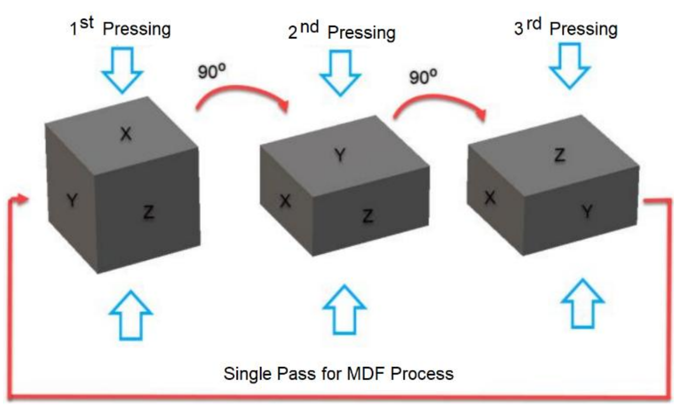

Fig. 1. Schematic representation of a single pass in the MDF process [26].

The Taguchi method was then used to analyze the contribution of each parameter and to identify the optimal combination for maximizing the effective strain, as numerous studies in the literature have demonstrated a strong correlation between increased effective strain and improvements in the mechanical properties of metallic materials [30, 31]. Therefore, maximizing ε_eff was considered a valid and meaningful optimization target in this study. The selected parameter combinations and the corresponding effective strain values obtained from DEFORM-3D simulations are summarized in Table II. In addition to the initial nine simulations, an additional DEFORM 3D analysis was performed using the optimal parameter set identified by the Taguchi method. The resulting effective strain value was first compared with those obtained from the original parameter combinations to validate the optimization result. Finally, the effective strain value obtained under the optimal MDF conditions was compared with equivalent values reported in the literature for other SPD techniques, particularly ECAP and twist extrusion, in order to assess the relative efficiency of the MDF process applied to AA6082.

III. Results and Discussion

The effective strain (ε_eff) values obtained from the finite element simulations are presented in Table II. As shown in the table, the lowest ε_eff value was 0.522 mm/mm, while the highest value reached 1.566 mm/mm. These strain levels are generally lower than those typically reported in ECAP-processed samples [10, 30]. And, the maximum effective strain was achieved at a forming temperature of 20 °C. When compared with ECAP processes carried out at similar temperatures, the strain levels observed in this study are somewhat lower, yet not negligible. This difference can be attributed to two main factors: first, the reduction ratio applied in this study was significantly lower, and second, the results were derived from a single-pass deformation only.

Despite this, the obtained strain values clearly demonstrate the capability of the MDF process to induce substantial plastic deformation under relatively simple processing conditions. Furthermore, the process can be performed at room temperature, potentially removing the need for any thermal input when optimal parameters are applied. This could result in considerable energy savings and shorter cycle times. Although the optimal parameter set will be discussed in detail through the Taguchi analysis in the following sections, the present results already highlight the potential of MDF as a promising SPD method, especially in contexts where reduced thermal requirements and simplified processing are desirable.

TABLE II: Finite Element Analysis Parameters and Results

Dimensions (mm)	**Temperature (ºC)**	**Height Reduction (%)**	**Effective Strain (mm/mm)**
10x10x10	200	5	0,522
10x10x10	100	10	0,957
10x10x10	20	20	1,566
10x10x20	200	10	0,783
10x10x20	100	20	1,392
10x10x20	20	5	0,609
10x10x40	200	20	1,131
10x10x40	100	5	0,522
10x10x40	20	10	0,870

According to the results of the Taguchi analysis (Table III), the height reduction was identified as the most influential parameter on effective strain. This finding is consistent with physical expectations, as a greater reduction per pass imposes higher stress on the material, leading to more intense plastic deformation and, consequently, greater alterations in grain structure as expected.

Forming temperature, on the other hand, exhibited a typical influence similar to that observed in other SPD techniques. While it facilitates deformation by reducing flow stress, its effect on the final effective strain was less dominant than that of height reduction.

In contrast, the billet geometry, which was expected to play a significant role due to its aspect ratio, especially in non-cubic shapes, was found to be the least influential parameter. Given that longer samples were assumed to exhibit greater localized strain under uniaxial compression, it was hypothesized that a rectangular prism geometry would enhance the deformation level. However, the results indicated otherwise, suggesting that geometry had minimal impact compared to height reduction and temperature.

TABLE III: Response Table for Means

Level	Dimensions	Temperature	Height Reduction (%)
1	1,0152	0,8122	0,5511
2	0,9282	0,9572	0,8702
3	0,8412	1,0152	1,3363
Delta	0,1740	0,2030	0,8122
Rank	3	2	1

As a result of the Taguchi optimization process, the signal-to-noise (S/N) ratios corresponding to each level of the selected parameters were calculated based on the "larger is better" criterion. The outcomes of this analysis are presented in Table IV and Fig 2. According to these results, it is possible to draw several important conclusions regarding the relative influence of the process parameters on effective strain. The following section provides a detailed interpretation of these findings.

TABLE IV: Response Table for Signal to Noise Ratio

Level	Dimensions	Temperature	Height Reduction (%)
1	–0.7092	–2.2324	–5.1986
2	–1.1849	–1.0502	–1.2370
3	–1.9273	–0.5388	2.6143
Delta	1.2181	1.6936	7.8129
Rank	3	2	1

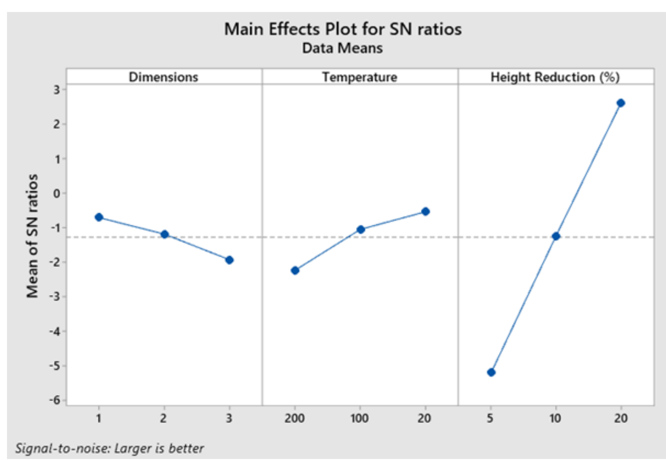

Fig 2. S/N Ratio plots

According to the results of the Taguchi analysis, height reduction (%) was identified as the most influential factor affecting the effective strain output. This outcome is consistent with the fundamental principles of plastic deformation, as

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greater material compression per pass directly leads to more intense strain accumulation and a higher degree of microstructural refinement.

The analysis also revealed that *the optimal combination of parameters for maximizing effective strain includes the smallest billet geometry (10×10×10 mm), the lowest forming temperature (20 °C), and the largest height reduction ratio (20%).* Among all tested combinations, this specific parameter set yielded the highest average ε_eff value. The use of a compact billet appears to support more uniform and concentrated deformation, while the elevated temperature lowers flow stress and the higher reduction ratio intensifies strain input per pass.

These findings were further confirmed through a validation simulation conducted using the optimal parameter set. The resulting effective strain value not only aligns with the Taguchi prediction but also highlights the potential of the MDF process to deliver significant plastic deformation under strategically selected processing conditions.

The FEA result corresponding to the optimal parameter combination is illustrated in Fig. 3. The effective strain value obtained under these conditions was the highest among all simulations and aligns well with the observed trends in parameter influence, thereby confirming the validity of the optimization process. Although the strain levels achieved are somewhat lower than those typically reported in traditional SPD methods such as ECAP or HPT [20, 30, 32, 33], they are nonetheless comparable. More importantly, the MDF process offers notable advantages, including the ability to operate at lower temperatures and with simpler tooling and processing steps, which enhances its industrial applicability.

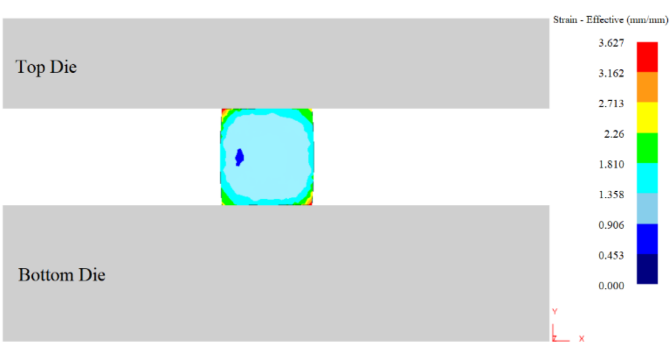

Fig 3. Distribution of effective strain obtained from the FEA simulation based on the optimum parameter combination.

Upon examination of the distribution presented in Fig. 3, the average effective strain exceeds 1.8 mm/mm, which is notably higher than the maximum strain value obtained among the combinations. This outcome not only confirms the validity of the Taguchi-based optimization but also highlights the capability of the MDF process to generate intense and uniform plastic deformation when the process parameters are properly selected. The relatively homogeneous strain distribution across the sample, as shown by the light blue regions in Fig. 3, further confirms the effectiveness of the optimized configuration and indicates strong potential for the development of enhanced mechanical properties under these conditions.

IV. Conclusion

This study investigated the applicability and deformation efficiency of the multi-directional forging (MDF) process on AA6082 alloy through finite element simulations and Taguchi-based optimization. Based on the analyses and findings, the following conclusions can be drawn:

- The effective strain (ε_eff) values obtained from simulations ranged between 0.522 mm/mm and 1.566 mm/mm, depending on the process parameters.
- Among the three investigated factors (billet dimensions, forming temperature, and height reduction (%)) the height reduction was identified as the most influential parameter on effective strain.
- The optimal parameter combination determined by Taguchi analysis was: smallest billet size (10×10×10 mm), highest forming temperature (20 °C), and highest reduction ratio (20%).
- The effective strain value obtained under the optimal conditions exceeded 1.8 mm/mm, aligning well with expected trends and further confirming the reliability of the optimization approach.
- While the strain levels were slightly lower than those typically obtained by conventional SPD methods like ECAP, the MDF process still delivered comparable results, with the added benefit of simplified die design and lower temperature requirements.

These findings demonstrate that the MDF method, even when optimized through a simple Taguchi design, can serve as a viable alternative for severe plastic deformation, especially in applications where process simplicity, reduced thermal input, and energy efficiency are critical.

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