FINITE ELEMENT ANALYSIS OF GRAIN SIZE MICROSTRUCTURE OPTIMIZATION IN HOT FORGING PROCESS PARAMETERS OF A STEEL WORKPIECE: EFFECTS OF TEMPERATURE AND DEFORMATION SPEED

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Abstract: *This study explores the optimization of hot forging process parameters for a steel component, focusing on the influence of grain size microstructure. Utilizing finite element analysis, the research examines how variations in the forging temperature and deformation speed impact the final properties of the steel. By adjusting these parameters, the study aims to enhance mechanical strength and durability through controlled grain refinement. Results indicate that specific temperature and speed settings can significantly optimize grain size distribution, thus improving the component's performance. This research provides valuable insights for manufacturing industries aiming to optimize forging processes for better material characteristics and operational efficiency.*

Keywords: *microstructure, grain size, forging, finite element*

1. Introduction

The evolution of microstructure (viewed as structural changes on a microscopic scale) plays a fundamental role in influencing material properties during the hot forming process. Previous research in this field enables us to develop semi-empirical and physico-metallurgical models for microstructure simulation with the support of finite element (FE) analysis. This paper will introduce the fundamental knowledge of microstructural mechanisms, microstructure formulations in hot forming, and several applied models in Simufact. The field of optimizing hot forging processes for steel components has seen a significant advancement through a combination of experimental and computational approaches, as evidenced by the recent science papers.

Jimenez et al. Ref. [1] explores the microstructure changes in hot bar stretching, focusing on the rapid evolution of austenite grain size and employing three-dimensional finite element modeling for analysis.

Dourandish et al. Ref. [2] investigates the deformation and microstructure evolution in martensitic stainless steel, utilizing finite element simulations to model strain, temperature distribution, and dynamically recrystallized grain size across large industrial-scale forgings.

Huang et al. Ref. [3] consider into the optimization of the hot forging process for helical gears with clutch gears used in automobile transmissions, using response surface methodology to optimize the parameters influencing microstructure characteristics like recrystallization fraction and grain size.

In the paper Ref. [4], Moraes et al. extends the study to specific automotive components, demonstrating how dynamic recrystallization impacts the gear forging process through detailed numerical simulations.

This study Ref. [5] develops a three-dimensional finite element (FE) model that combines thermo-mechanical aspects with microstructure evolution, specifically focusing on 20CrMnTiH steel used in helical gear manufacturing. It explores how dynamic recrystallization (DRX) and grain refinement are influenced by deformation temperature during the hot forging process. The results highlight that higher deformation temperatures facilitate dynamic recrystallization and lead to finer grain sizes. The research indicates that the dynamic recrystallization mostly occurs in regions of high plastic deformation, like the addendum and dedendum of gears, and less so in other areas.

2. Numerical Model

In hot forming processes, recovery, recrystallization, and grain growth are the three primary mechanisms responsible for microstructural changes. Recovery involves the annihilation and rearrangement of dislocations and typically does not impact the grain boundaries. Recrystallization, on the other hand, takes place at the grain boundaries and is driven by stored energy, where it consumes the original grains and forms new dislocation-free grains. Grain growth, both normal and abnormal, is driven by boundary energy, which promotes the elimination of smaller grains, ultimately reducing the grain boundary area to achieve a lower energy configuration.

Microstructure evolution can be divided into:

- **Dynamic changes**: dynamic recovery (DRV) and dynamic recrystallization (DRX);
- **Static changes**: static recovery (SRV), static recrystallization (SRX), and grain growth (GG).

Finite element (FE) analysis of metal deformation processes offers localized conditions that can be utilized in microstructure simulations based on the aforementioned formulations. The most common approach to integrating microstructure simulation into FE analysis is to account for the impact of microstructures on mechanical properties, such as yield stress, where the stresses determined from the microstructure simulation are incorporated into the FE analysis.

The workpiece material AISI 1030 steel has been used in this simulation and Table 1 shows the chemical composition.

Table 1: *AISI 1030 chemical composition (%)*

Chemical composition (percentage mass portion)

Element	Minimum	Maximum	Fixed value
C	0.27	0.34	0.3
Fe	98.67	99.13	99.1
Mn	0.6	0.9	0.6
P	0	0.04	0

Thermo-mechanical properties

Thermo-mechanical properties of the AISI 1030 can be seen in Table 2.

Table 2: *AISI 1030 thermo-mechanical properties*

SAE 1030		
Chemical composition: C=0.30%, Mn=0.75%, P=0.04		
Property	**Value in metric unit**	
Density	7.872 *10³	kg/m³
Modulus of elasticity	200	GPa
Thermal expansion (20 °C)	$11.7*10^{-6}$	$°C^{-1}$
Specific heat capacity	486	J/(kg*K)
Thermal conductivity	48.7	W/(m*K)
Electric resistivity	$1.66*10^{-7}$	Ohm*m
Tensile strength (hot rolled)	470	MPa
Yield strength (hot rolled)	260	MPa
Elongation (hot rolled)	20	%
Hardness (hot rolled)	75	RB
Tensile strength (cold drawn)	525	MPa
Yield strength (cold drawn)	440	MPa
Elongation (cold drawn)	12	%
Hardness (cold drawn)	80	RB

The YADA model is incorporated into the Simufact Forming software, which is utilized for analyzing the forging process. This model is based on the research conducted by H. Yada et al. Ref. [10] in 1983. Through a series of experiments involving high-speed multi-step forming processes, Yada developed this empirical model to describe microstructure evolution, including static softening.

$$\begin{cases} \varphi_{growth} = C_1 \cdot e^{\frac{C_2}{T}} \\ g = g_0, \; \varphi<\varphi_{growth} \\ g = -C_3 \cdot \dot{\varphi}^{-C_4} + e^{\left(-C_5 \cdot \frac{Q}{R \cdot T}\right)}, \; \varphi>\varphi_{growt} \end{cases} \quad (1)$$

where:

φ_{growth} - strain for the variation of grain size;

g_0 - initial grain size;

$\dot{\varphi}$ - average strain rate;

Q - activation energy for grain growth;
C1, C2, C3, C4, C5 - material dependent coefficients.

In Table 3 can be seen the values of these parameters for the material that was used in the simulation. The method for determining these parameters is not provided by the Simufact Forming Software.

Table 3. *Parameters in the YADA model of base metal*

	g_0	C_1	C_2	C_3	C_4	C_5	Q
1030	180	22600	0.27	0.27	0.0002	8000	267000

The 3D CAD model is shown in Fig. 1.

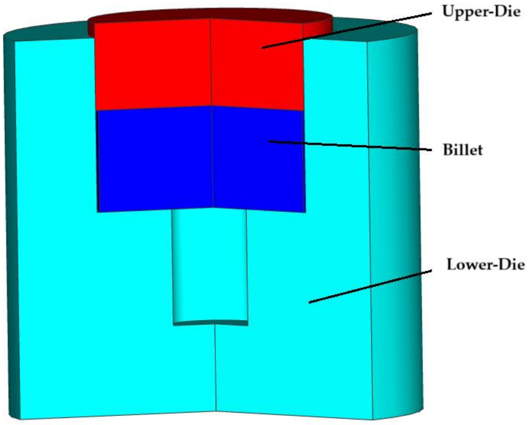
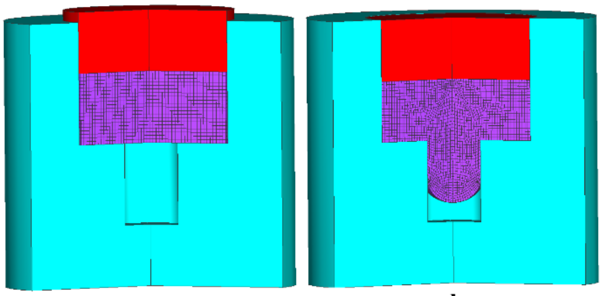


Figure 1: *3D CAD model*

In finite element analysis (FEM) of a forging process, remeshing is a critical operation used to improve mesh quality and accuracy. During the forging process, large deformations can distort the initial mesh, leading to poor element shapes and decreased accuracy in stress and strain predictions. Remeshing regenerates the mesh, adjusting it to better conform to the deformed geometry of the workpiece. This process ensures that the mesh elements remain well-shaped and distributed, allowing for a more stable and precise analysis. Remeshing is especially useful in high-deformation processes like forging, where maintaining mesh quality is essential for reliable results. In the next step, the initial mesh of the workpiece was created and the parameters for the remeshing procedure were defined. The initial edge length was set to 1.5 mm (see Fig.2) and the remeshing criteria was for strain change to a value of 0.4.



a **b**

Figure 2: *3D finite elements model: a-initial mesh; b-remeshed workpiece*

In the finite element analysis (FEM) of the forging process, establishing accurate contact between the workpiece and the die is essential for realistic simulation results. Contact modeling defines the interaction and boundary conditions between the workpiece and the die, ensuring that forces, pressures, and frictional effects are correctly captured. Properly defining contact helped for predicting material flow, stress distribution, and potential defects in the forged part. In forging, where high pressures are applied, accurate contact modeling allowed the FEM to realistically represent the behavior of material under extreme deformation, making it crucial for reliable process optimization and part quality assessment.

The parameters used for the considered cases to realize the forging process can be seen in Table 4.

Table 4. *Parameters for the forging processes*

Case	**Velocity [mm/s]**	**Billet temperature [°C]**
1	30	700
2	35	700
3	40	700
4	30	800
5	35	800
6	40	800
7	30	900
8	35	900
9	40	900
10	30	1000
11	35	1000
12	40	1000
13	30	1100
14	35	1100
15	40	1100

3. Results

The values of the equivalent stresses, strains and the minimum value of the size of the grains, obtained in the 15 cases, can be seen in Table 5.

Table 5. *Stress, plastic strain and grain size*

Case	σ_{eq} [MPa]	ε_p	g [μm]
1	257	7.69	3.34
2	246	7.57	2.18
3	229	7.31	1.54
4	209	6.87	4.22
5	182	6.28	5.36
6	252	7.85	3.08
7	239	7.71	1.35
8	225	7.44	0.49
9	204	7.01	3.98
10	180	6.46	5.14
11	262	7.99	3.65
12	253	7.88	2.55
13	238	7.58	2.06
14	216	7.15	4.41
15	186	6.54	5.51

The Fig. 3 displays the strain distribution and the corresponding strain history for three specific points in a workpiece undergoing forging. In the top section, can be seen a map representing the strain distribution across the workpiece: point 1 is located in the highly deformed region near the edge where significant strain is visible, point 2 is in a moderately deformed area, and point 3 is in a region with minimal deformation. The graph details the strain history over time at these points: point 2 exhibits the highest strain increase over time, followed by point 1 with a moderate but steady increase, and point 3 showing very little change, indicating it undergoes the least deformation during the process. This kind of analysis helps in understanding the mechanical behavior of materials under stress, critical for optimizing forging processes and improving material performance. Fig. 4 provided illustrates the distribution of grain size and its variation over time at three specific points on a workpiece after a forging process. The top part of the image shows a color gradient indicating grain size distribution: the blue areas have smaller grains, while red and orange areas have larger grains. Point 1, situated near a corner, is in the blue region suggesting smaller grain size; point 2, slightly away from the corner, is in the orange area indicating larger grains; and point 3, further from the corner, is in the red area, indicating the largest grain sizes.

The graph quantitatively presents the changes in grain size at these points over time. Point 1 shows a rapid increase in grain size which then stabilizes, point 2 experiences a sharp and immediate increase in grain size, likely indicating dynamic recrystallization during forging, and point 3 exhibits a gradual and consistent increase in grain size, which may suggest progressive strain-induced grain growth. This information is crucial for assessing the effects of forging conditions on material properties, particularly how grain size evolves, which is critical for understanding the material's final mechanical properties.

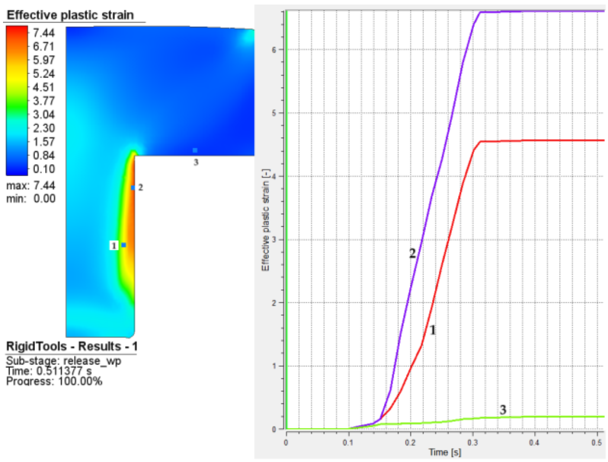


Figure 3: *Distribution and plot of strain*

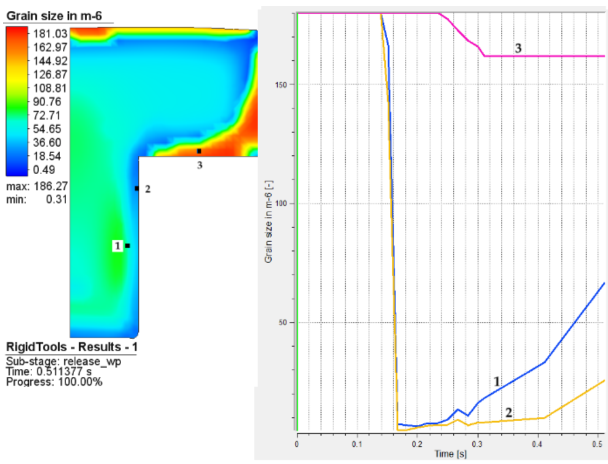


Figure 4: *Distribution and plot of grain size*

The series of figures from 5 to 7 presents the effects of temperature on various mechanical properties at different strain rates during a forging process.

Fig. 5 figure shows that the equivalent stress decreases with increasing temperature across all strain rates (30 mm/s, 35 mm/s, and 40 mm/s). The decrease in stress with temperature is a common behavior in materials, indicating reduced strength and increased ductility at higher temperatures. Fig. 6, similar to the trend observed for stress, the plastic strain decreases as the temperature increases. This trend is consistent across all tested strain rates. The reduction in plastic strain with increased temperature could be attributed to the material becoming more ductile, allowing it to deform more easily without accumulating large strains. Fig. 7 shows a non-linear relationship between grain size and temperature. Initially, as the temperature increases from 700°C to approximately 850°C, grain size decreases, indicating possible grain refinement mechanisms such as dynamic recrystallization. However, beyond 850°C, grain size starts to increase, likely due to grain growth as the temperature provides the energy necessary for grain boundary migration. This trend is consistent across all strain rates, with slight variations in grain size depending on the rate of strain applied. These results provide valuable insights into how temperature and strain rate influence the mechanical properties and microstructural characteristics of a material during forging, important for optimizing process parameters.

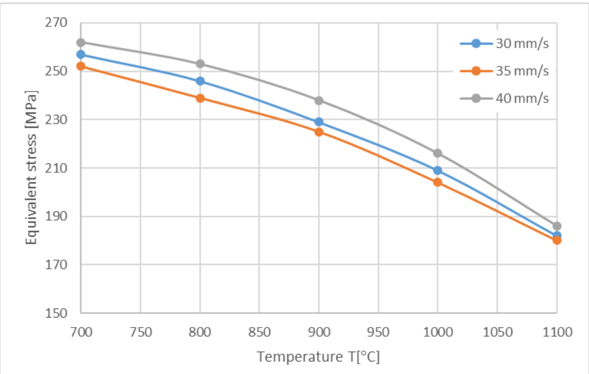


Figure 5: *Effect of temperature on equivalent stress at different strain rates*

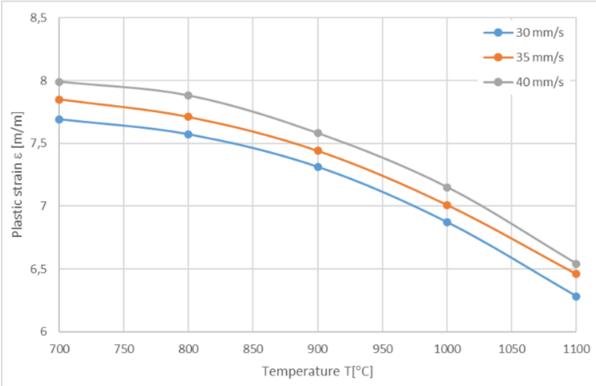


Figure 6: *Effect of temperature on plastic strain at different strain rates*

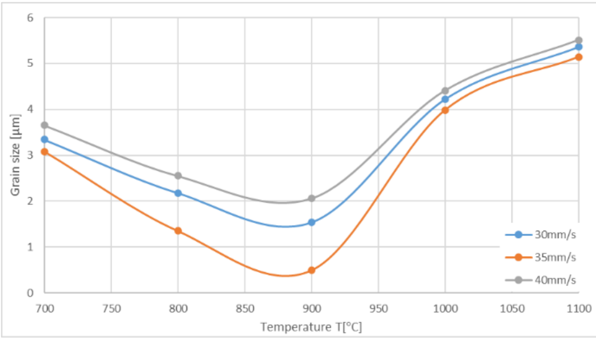


Figure 7: *Effect of temperature on grain size at different strain rates*

4. Conclusions

This study highlights the significant impact of temperature and deformation speed on grain size distribution in hot forging processes for steel components, as revealed through finite element analysis. The results demonstrate that higher forging temperatures facilitate grain refinement through dynamic recrystallization up to an optimal point, beyond which grain growth occurs due to increased energy at grain boundaries. Lower strain rates combined with controlled temperature settings lead to more uniform and finer grain structures, enhancing the mechanical properties of the forged steel.

The analysis also confirms that microstructural evolution, including dynamic and static recrystallization and recovery mechanisms, is crucial for achieving the desired mechanical characteristics. By fine-tuning these process parameters, it is possible to optimize the grain size distribution, resulting in improved strength, durability, and overall performance of the final product.

The findings suggest that integrating microstructure simulation within finite element models allows for precise adjustments in forging conditions to achieve specific material properties. This approach offers practical insights for optimizing hot forging processes, directly benefiting the manufacturing industry in producing components with enhanced structural integrity.

In future research, further refinement of the microstructure simulation models could yield even more accurate predictions of material behavior under varied processing conditions, advancing the capabilities of current manufacturing practices.

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