HOT WORKABILITY OF Ni-Fe HIGH-TEMPERATURE ALLOY

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The present work explores the hot workability window of a Ni-Fe (Ni 40-45%, Cr 11-14%, Mo 5-7%, Ti 2.35-3.10%) high temperature alloy to identify patterns with microstructural changes and hot forgeability as a function of temperature. Wedge-compression specimens made of a precipitation-strengthened Ni-Fe high-temperature alloy were compressed at initial temperatures of 940, 1050 and 1100 °C under industrial press conditions, and the microstructural response was evaluated correspondingly. The industrial-scale experiment was complemented with Finite-element modelling to estimate local equivalent strain and strain rate. The results of the current work indicated that the specimens deformed at 1050°C and 1100°C displayed a strong refining process in which grain size evolved from ASTM #6 to ASTM #10 whereas the finite-element modelling (FEM) revealed that the three specimens developed local equivalent strains larger than 2 even tough including the specimen deformed at 940°C in which no relevant recrystallization was observed. The results show that equivalent strain alone does not describe the observed microstructural response and that temperature and local deformation history must be considered jointly. The combined wedge-test/FEM approach provides a practical method for relating local deformation conditions to microstructural evolution and hot workability under industrially representative forging conditions.

KEYWORDS: NI-FE HIGH-TEMPERATURE ALLOY - HOT WORKABILITY - WEDGE-COMPRESSION TEST - HOT FORGING – RECRYSTALLIZATION - FINITE-ELEMENT MODELING

INTRODUCTION:

Ni-Fe superalloys are used for the fabrication of forged components for turbine applications with a maximum service temperature of around 600°C. The alloy exhibits excellent microstructural stability at elevated temperatures which results in excellent resistance to mechanical loading under both static and dynamic conditions, good corrosion, creep, stress-rupture strength and good resistance under thermal cycling. However, the trade-off from a manufacturing perspective is that the processing window demands careful control of hot working and heat treatment parameters to develop an optimal microstructure, reduce the presence of detrimental phases and ensure target mechanical properties. The manufacturing route of this material may include combinations of remelting techniques along with open-die forging, ring rolling, heat treatment, and machining [1].

Hot working is therefore a critical stage in the processing of these alloys. Temperature, strain and strain rate influence material flow, recovery, and recrystallization during deformation. Hot-compression studies on Ni-Fe alloys with compositions like the alloy investigated in this work have shown that deformation temperature and strain rate strongly affect flow behavior and microstructural evolution. Processing maps have also been used to identify favorable hot-working conditions [2]. However, conventional compression tests can be expensive, and time consuming, since these types of testing require specialized hot compression equipment as well as uniform and controlled laboratory conditions. Even considering its limitations (heterogeneous distributions of strain and strain rate along the specimen), Wedge testing represents a rapid and practical alternative, as it is conducted directly on the selected production forging line, thereby enabling a direct evaluation of the actual industrial-scale conditions providing representative real-life process information. The above bearing in mind that the forging sector operates under stringent time-to-market constraints, as customers require short lead times and competing firms continuously shorten their own development cycles for new alloys. Finally, to compensate for the aforementioned limitations, the experimental model is combined with FEA simulations to estimate local equivalent strain and strain rates

The wedge-compression test provides an alternative approach for investigating such heterogeneous deformation. Because specimen height varies along its length, compression between flat dies generates a range of local deformation conditions within a single specimen. Parsa et al. [3] combined wedge testing with numerical simulation to correlate local deformation with microstructural changes and hot workability, demonstrating that different regions of the specimen can exhibit markedly different microstructural responses. More recently, Rosiak et al. [4] used a similar approach to investigate the relationship between deformation, microstructural evolution, and hot forgeability at different temperatures. These studies demonstrate the potential of wedge testing to provide hot-workability information while highlighting the need for numerical analysis to quantify the heterogeneous local deformation conditions. In the present work, wedge-compression testing was applied to a precipitation-strengthened Ni-Fe high-temperature alloy under industrially representative conditions. Tests were conducted at initial temperatures of 940, 1050 and 1100 °C under the same nominal press condition, and the microstructural response was evaluated at five longitudinal positions. Finite-element modeling was used to determine the corresponding local equivalent strain and strain rate. The objective was to correlate the experimentally observed microstructural evolution with the heterogeneous local deformation conditions and to assess the capability of the wedge-compression approach to provide practical hot-workability information under industrially representative forging conditions.

Physical Metallurgy of the selected Alloy.

The selected alloy is a precipitation-strengthened iron-nickel-base superalloy designed for structural applications requiring high tensile and creep strength at elevated temperatures (up to ~595 °C / 1100 °F). Its principal strengthening mechanism is precipitation of the ordered intermetallic gamma prime phase (γ') [Ni_3(Ti,Al)] from a γ gamma face-centred cubic (FCC) austenitic matrix, supplemented by solid-solution hardening from molybdenum and iron. Ring rolling is the dominant near-net-shape forming route for turbine discs, spacer rings, structural flanges, and seal retainers.

Summary of Phases present in the selected alloy:

γ gamma face-centred cubic (FCC) austenitic matrix
γ', Gamma Prime, Ni_3(Ti,Al), $L1_2$ (ordered FCC), Primary strengthening precipitate
δ, Delta, Ni_3Ti, Orthorhombic ($D0_a$), Grain size control via Zener pinning
η, Eta, Ni_3Ti, Hexagonal ($D0_{24}$), Embrittling GB phase — generally harmful

1. MATERIALS AND METHODS

1.1. Material

The investigated material was a precipitation-strengthened Ni-Fe high-temperature alloy with an approximate composition of 40–45 wt.% Ni, 11–14 wt.% Cr, 5–7 wt.% Mo and 2.35–3.10 wt.% Ti. The material was obtained from an industrially processed billet in the condition used for subsequent forging operations. Prior to wedge testing, the initial microstructure was characterized by optical microscopy to establish the reference microstructural condition for comparison with the deformed specimens.

1.2. Wedge-compression test

Low End Forging Temperature 940°C (Below δ solvus < 960 °C): Delta δ precipitates at grain boundaries, restricting migration and producing fine equiaxed recrystallized grains (ASTM 8 or finer) potential γ' re-precipitation is rapid; flow stress increases sharply and cracking risk escalates.

Optimal Forging Temperature Recommended 1050°C : Gamma Prime γ' dissolves completely, enabling maximum workability and DRX without precipitate pinning.

High End Forging Temperature 1100°C (above 1100 °C): Risk of incipient melting at Ni-Ti-rich grain boundary films — permanent embrittlement even after re-heat-treatment.

Wedge specimens were machined from the industrially processed billet with a nominal length of 150 mm and a maximum height of 50 mm. The geometry consisted of an initial constant-height region, a tapered section and a 20-mm-high terminal region, as shown in Fig. 1. The specimens were heated to 940, 1050 or 1100 °C and held at the test temperature for 1 h prior to deformation. Temperature was monitored using a Type-K thermocouple embedded 1 in. deep in a 4 × 4 in. reference section subjected to the same heating cycle as the wedge specimens.

Compression was performed between flat dies in a 3000-ton press at a programmed ram velocity of 10 mm/s throughout the stroke. The final die position was set to a height of 20 mm, corresponding to the minimum initial height of the wedge. Ceramic-fiber insulation was used to reduce heat loss during transfer and deformation.

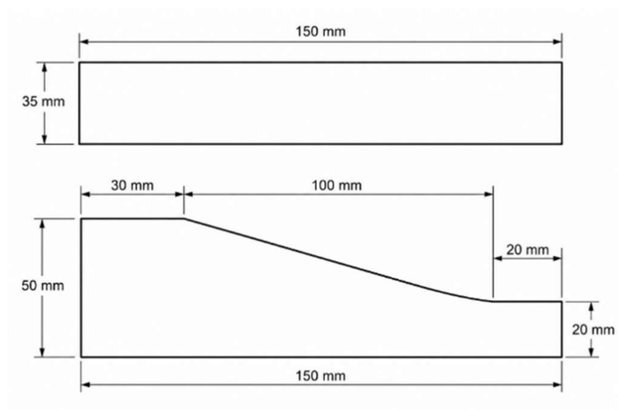

Fig. 1 - Geometry and dimensions of the wedge specimen used in the compression tests.

1.3. Microstructural characterization and image analysis

Prior to deformation, the initial microstructural condition was characterized by replica metallography obtained from the wedge surface. Following compression, each wedge was sectioned longitudinally, and five transverse sections were extracted along the specimen length, corresponding to locations M1–M5. Metallographic observations were performed near the mid-height of the locally deformed specimen thickness. The samples were prepared using conventional metallographic procedures, etched with Kalling's reagent, and examined by optical microscopy at 100X magnification.

The recrystallized area fraction was estimated by quantitative analysis of the optical micrographs. Recrystallized regions were first identified based on their metallographic morphology relative to the initial microstructural condition. Full-field micrographs were then converted to 8-bit images and intensity thresholding was used to assist segmentation of regions exhibiting the identified recrystallized morphology. The corresponding area fraction was quantified from the segmented images and reported as X_{RX}.

1.4. Finite-element analysis

The wedge-compression tests were simulated using FORGE® NxT 4.1. A three-dimensional finite-element model was constructed using the experimental wedge geometry and a material model representative of the investigated Ni–Fe high-temperature alloy. The specimen was positioned between a fixed lower die and a moving upper die. The upper die moved at a constant velocity of 10 mm/s and a total displacement of 30 mm, resulting in a final specimen height of 20 mm. Simulations were performed for initial workpiece temperatures of 940, 1050 and 1100 °C, reproducing the experimental test conditions. No lubrication was defined at the die workpiece interfaces.

The workpiece was discretized using a volumetric finite-element mesh with a minimum mesh size of 1 mm, with remeshing activated during deformation. Numerical results were evaluated at five locations corresponding to the experimental metallographic sampling positions M1–M5. The local equivalent-strain and strain rate histories were extracted throughout deformation, and the maximum values reached at each location were defined as the maximum equivalent strain, $\varepsilon_{e}q,max$, and maximum strain rate, $\dot{\varepsilon}max$, respectively. These parameters were subsequently correlated with the experimentally estimated recrystallized area fraction, X_{RX}.

2. RESULTS AND DISCUSSION

2.1. Macroscopic deformation and sampling strategy

Wedge compression produced a heterogeneous deformation profile along the specimen length, as expected from the continuously varying initial height. Five locations, designated M1–M5, were selected along the deformed wedge for microstructural characterization (Fig. 2). The metallographic observations were performed near the mid-height of the locally deformed thickness, and the corresponding locations were evaluated in the finite-element model. This approach enabled the microstructural response at each position to be directly compared with its local deformation history. Importantly, the sampling sequence does not represent a progresive increase in deformation, since the local equivalent strain and strain rate depend on both position and the material flow developed during compression.

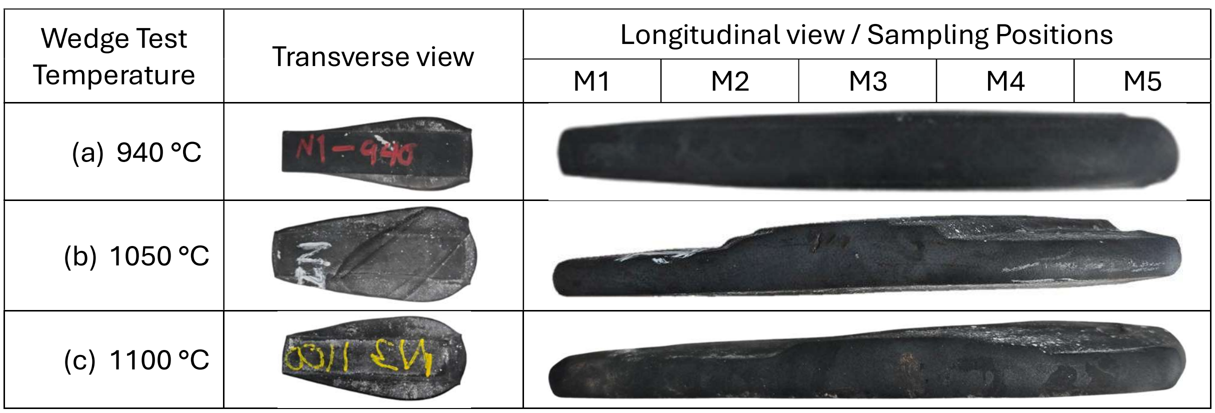

Fig. 2 - Macroscopic appearance of the wedge specimens after compression at (a) 940 °C, (b) 1050 °C, and (c) 1100 °C, showing the longitudinal locations of the M1–M5 metallographic samples.

2.2. Initial microstructural condition

The initial microstructure of the wedge specimen prior to compression is shown in Fig. 3. Optical metallography revealed a predominantly equiaxed grain morphology with an ASTM grain size No. 6. This condition was used as the microstructural reference for comparison with the specimens after wedge compression.

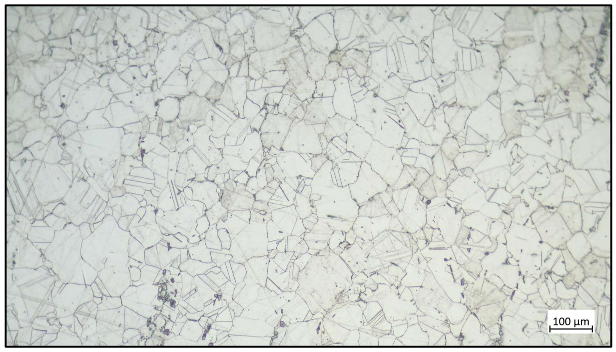

Fig. 3 - Initial microstructure of the wedge specimen prior to compression, showing an ASTM grain size No. 6.

2.3. Microstructural evolution at 940°C

At 940 °C, the microstructure exhibited a progressive change in grain morphology across the wedge specimen (Fig. 4). M1 and M2 retained a predominantly equiaxed morphology relatively similar to the initial condition, whereas increasing grain distortion and elongation were observed at M3–M5. The effect was particularly evident at M4, corresponding to the location with the highest predicted equivalent strain.Despite these differences in deformation morphology, no recrystallized area was identified by the image-analysis procedure at any of the five locations (X_{RX} =0%). This occurred over a wide range of local deformation conditions, with the maximum equivalent strain ranging from 0.018 at M1 to 2.572 at M4. Thus, at 940 °C, increasing local deformation produced pronounced grain distortion but did not result in a detectable recrystallized morphology under the investigated conditions.

2.4. Microstructural evolution at 1050°C

At 1050 °C, the microstructural response varied significantly along the wedge specimen (Fig. 4). M1 and M2 retained a predominantly deformed grain morphology, with recrystallized area fractions of 4% and 14%, respectively. In contrast, M3 and M4 exhibited the highest recrystallized area fractions, reaching 96% and 93%, together with a markedly refined microstructural appearance. At M5, the recrystallized area fraction decreased to 64%, and a mixed morphology consisting of refined regions and elongated deformed grains was observed.The recrystallized area fraction increased from M1 to M3 and then decreased toward M5, indicating that the microstructural response cannot be described solely by the magnitude of the local equivalent strain. Although M3 and M4 showed extensive recrystallization, the decrease observed at M5 suggests that the local deformation history, including the combined effects of equivalent strain and strain rate, must be considered when interpreting the microstructural response.

2.5. Microstructural evolution at 1100°C

At 1100 °C, the microstructural response varied considerably along the wedge specimen (Fig. 4). M1 retained a predominantly deformed grain morphology, with a recrystallized area fraction of only 2%. The recrystallized fraction increased at M2 and M3 to 27% and 59%, respectively, accompanied by a progressive development of refined regions within the deformed microstructure. The highest recrystallized area fraction was observed at M4, reaching 94%. At M5, however, the recrystallized fraction decreased to 42%, with the microstructure showing a combination of refined regions and elongated deformed grains.

The recrystallized area fraction increased from M1 to M4 and then decreased at M5, indicating that the microstructural response cannot be described solely by the magnitude of the local equivalent strain. The local deformation history, including the combined effects of equivalent strain and strain rate, must therefore be considered when interpreting the recrystallization response.

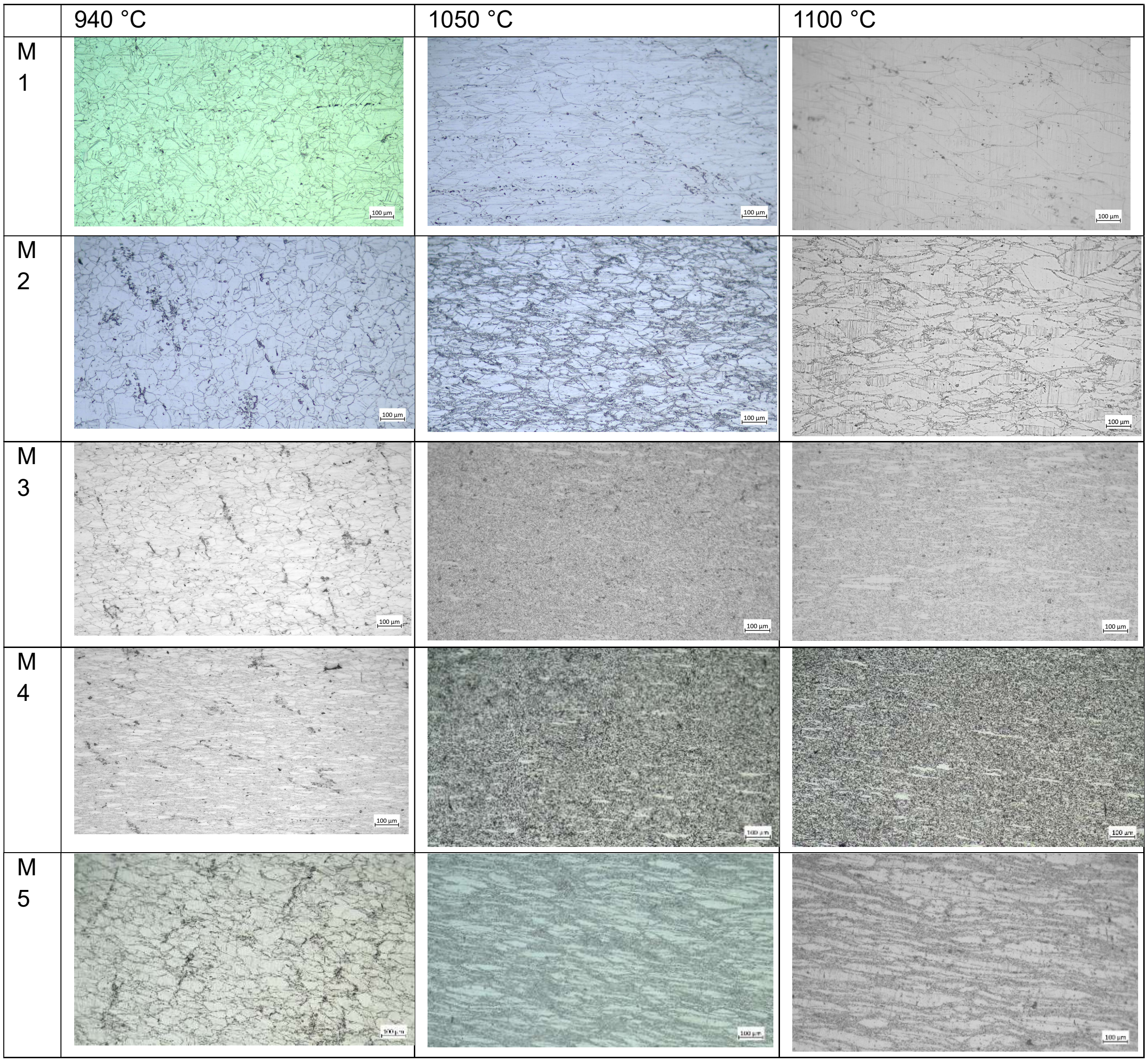

Fig. 4 - Optical micrographs at positions M1–M5 after wedge compression at 940, 1050, and 1100 °C.

2.6. Correlation between local deformation conditions and recrystallization

The relationship between the local deformation conditions and the recrystallized area fraction is summarized in Table 1. The FEM results show that the five sampling positions were subjected to different combinations of maximum equivalent strain and maximum strain rate. At 940 °C, no recrystallized regions were detected despite the wide range of local deformation conditions developed along the wedge. In contrast, substantial recrystallization occurred at 1050 and 1100 °C, particularly at M3 and M4.

Table 1 - FEM-predicted local deformation conditions and measured recrystallized area fraction at the M1–M5 sampling positions.

T	M1 $\varepsilon eq,max$ / $\dot{\varepsilon}max$ (s^{-1})	M2 $\varepsilon eq,max$ / $\dot{\varepsilon}max$ (s^{-1})	M3 $\varepsilon eq,max$ / $\dot{\varepsilon}max$ (s^{-1})	M4 $\varepsilon eq,max$ / $\dot{\varepsilon}max$ (s^{-1})	M5 $\varepsilon eq,max$ / $\dot{\varepsilon}max$ (s^{-1})	X_{RX} M1–M5
940 °C	0.018 / 0.087	0.227 / 0.227	0.771 / 1.680	2.572 / 2.476	1.927 / 0.908	0 / 0 / 0 / 0 / 0 %
1050 °C	0.026 / 0.110	0.250 / 0.250	0.883 / 1.740	2.472 / 2.496	1.751 / 0.837	4 / 14 / 96 / 93 / 64 %
1100 °C	0.030 / 0.122	0.262 / 0.262	0.924 / 1.776	2.394 / 2.456	1.873 / 0.814	2 / 27 / 59 / 94 / 42 %

As shown in Fig. 5, the recrystallized area fraction did not increase consistently with either maximum equivalent strain or maximum strain rate. For example, M5 showed a lower recrystallized area fraction than M3 and M4 at both 1050 and 1100 °C, despite being subjected to substantial local deformation. These results indicate that the observed microstructural evolution cannot be described by equivalent strain or strain rate individually. Instead, the combined effects of temperature, strain, and strain rate must be considered when interpreting the local recrystallization response.

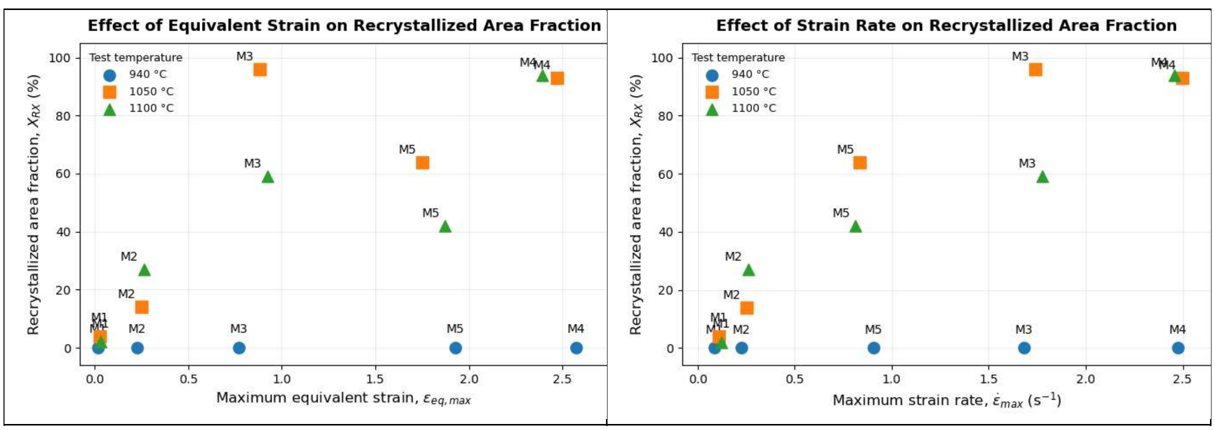

Fig. 5 - Relationship between recrystallized area fraction and local deformation conditions predicted by the finite-element model: (a) maximum equivalent strain and (b) maximum strain rate.

2.7. Effect of temperature and local deformation conditions on recrystallization

The combined experimental and finite-element results indicate that temperature strongly influenced the recrystallization response of the investigated Ni-Fe high-temperature alloy. At 940 °C, no measurable recrystallized area was identified, even at locations subjected to relatively high equivalent strain and strain rate. In contrast, substantial recrystallization was observed at 1050 and 1100 °C. This temperature dependence is consistent with previous hot-deformation studies on comparable Ni-Fe superalloys, where temperature and strain rate jointly influence the balance between deformation and microstructural restoration mechanisms [2].

The results also show that temperature alone does not fully describe the recrystallization response. At both 1050 and 1100 °C, the highest recrystallized area fractions occurred at M3 and M4, whereas M5 exhibited a lower recrystallized fraction despite its relatively high equivalent strain. This indicates that, at temperatures where recrystallization was observed, the local deformation history, including equivalent strain and strain rate, influences the extent of the microstructural response. This interpretation agrees with previous hot-deformation studies showing that recrystallization behavior is sensitive to the interaction between temperature and deformation rate [2].

From a methodological perspective, the heterogeneous deformation generated by the wedge specimen is particularly useful because a range of local deformation conditions can be investigated within a single test. Parsa et al. [3] similarly combined wedge testing with numerical simulation to evaluate microstructural changes and hot-workability conditions, while more recent work by Rosiak et al. [4] used the wedge-test approach to correlate deformation conditions with recrystallization and grain refinement. The present results extend this approach to an industrial-scale Ni-Fe high-temperature alloy and show that coupling wedge compression with finite-element predictions provides a practical method for identifying local deformation conditions associated with limited or extensive recrystallization.

CONCLUSIONS

- The results of the current work indicated that the specimens deformed at 1050°C and 1100°C displayed a strong refining process in which grain size evolved from ASTM #6 to ASTM #10 whereas the finite-element modelling (FEM) revealed that the three specimens developed local equivalent strains larger than 2, including the specimen deformed at 940°C in which no relevant recrystallization was observed.

- The results show that equivalent strain alone does not describe the observed microstructural response, and that temperature and local deformation history must be considered jointly. The combined wedge-test/FEM approach provides a practical method for relating local deformation conditions to microstructural evolution and hot workability under industrially representative forging conditions.

- It is also relevant to mention that no surface cracking was observed on the specimen deformed at 940°C considering the risk of cracking due to the potential presence of delta δ phase and gamma prime γ' re-precipitation also at 940 °C, no measurable recrystallized area was detected at any of the evaluated positions, despite the development of high local equivalent strain and strain rate. In contrast, substantial recrystallization occurred at 1050 and 1100 °C, indicating the strong influence of deformation temperature on the microstructural response. The recrystallized area fraction did not increase consistently with either maximum equivalent strain or maximum strain rate. The results therefore indicate that the observed recrystallization response must be interpreted considering the combined effects of temperature, strain, and strain rate rather than any individual deformation parameter.

Future Work

- Continue standardizing and enhancing the wedge testing as a practical tool to determine forging conditions under industrial scale conditions.

- Evaluate the influence of the prior microstructure obtained during the forging process on the final heat treatment stage.

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