FEM Analysis of Defects and Microstructure Evolution during Hot Working of Specialty Alloys

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Abstract. The main goals of process simulation in manufacturing are to reduce manufacturing/part development time and cost as well as increasing quality and productivity. In this study, porosity evolution is modeled by introducing a porosity evolution parameter, which is function of strain rate and stress triaxiality factor. Applicability is shown by simulating the first two stages of an ingot conversion process; variables are die geometry and bite size. Moreover, application is extended to hot shape rolling, where the geometry of the oval passes is the variable. Validation is carried out through evaluation of samples from final products. Also, surface defects in hot shape rolling are tracked by studying the instability during the rolling of the material. Plastic work approach was used to judge the occurrence of instability during the process. The effect of number of passes and roll gap was examined to predict the occurrence of surface cracking. On the other hand, unrecrystallized grains and coarse grain problem are other significant problems in the metalworking industry. A recrystallization model is implemented in a finite element framework, to study the effect of forging parameters on the microstructure evolution during ingot conversion process of a superalloy.

Keywords: Porosity, Surface Cracks, Grain Evolution, Hot Bar Rolling, Ingot Conversion, FEM Modeling.

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INTRODUCTION

Forging and hot shape rolling are high temperature metalworking process that supplies the raw material as billets or bars for subsequent forging, cold drawing and other down stream manufacturing processes. Lack of soundness and microstructure issues are the main quality problems in such manufacturing processes. Therefore, there is a need to continuously improve product quality, which is particularly true for high performance applications. Common metallurgical concerns associated with ingot conversion and hot rolling are unconsolidated porosity, surface defects, coarse grain and unrecrystallized grains. In some instances, these issues are discovered at the inspection stage, and not during the forming processes. Thus, many researchers have been investigating the cause of such defects using different approaches like fem analysis and experiments [1, 2].

The main objective of this work is to present the applicability of process modeling in the primary metalworking industry to understand the origin of various defects and to illustrate the use of FEM modeling to mitigate these defects. Conversion and hot bar rolling process are the metalworking processes chosen to study porosity consolidation, and surface cracks problems. Moreover, ingot conversion is the process used to study the effectiveness of various recrystallization models to predict grain size.

EXPERIMENTAL

Flow Stress and Recrystallization Behavior Determination

Efficient plastic deformation of a given material requires a through understanding of its mechanical and microstructural behavior during the metal forming process. Besides thermal properties, flow stress data at a given

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testing matrix is needed. Pyromet[1] 718 was chosen for this work, which is a precipitation hardenable nickel-chromium alloy. Flow stress data was obtained from two sources: JMatPro[2] [3] and hot compression testing, which was conducted under isothermal conditions at constant true strain rates of 0.001, 0.01, 0.1, 1, 5 and 20/s, and at temperatures from 850˚C to 1150˚C, in 50˚C steps.

RESULTS AND DISCUSSION

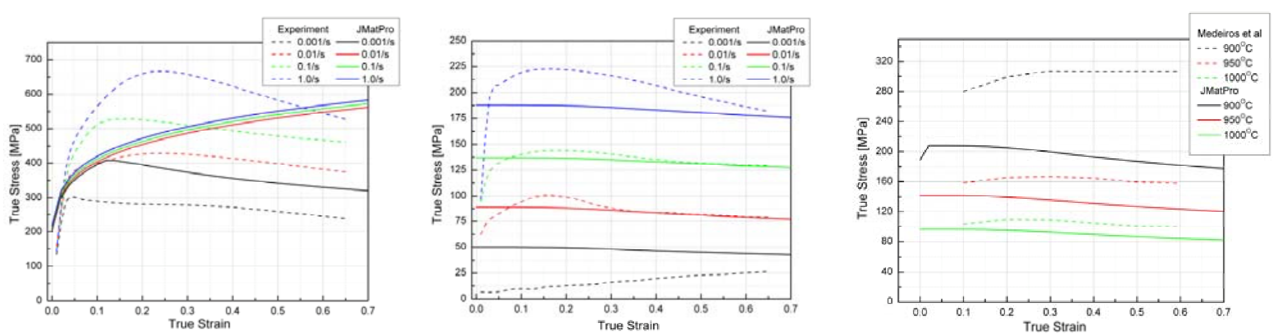
Stress-Strain Behavior

Typical stress-strain curves obtained at 850˚C and 1100˚C and a different strain rates are shown in Fig. 1a and b, respectively. The curves are corrected for deformation heating. The curves are of flow softening type in which the flow stress reaches a peak at a critical strain and decreases with further strain. In all the cases except for strain rate of 1.0 s^{-1}, the flow stress reaches a steady state at strains greater than about 0.4. For comparison, the plots show both experimental and modeling data from JMatPro.

Analysis of the flow stress data shows that at strain rates of below 0.1/s, flow stress is completely controlled by creep. At 1/s, the alloy first yields plastically via dislocation glide. It then work hardens rapidly up to a peak stress, and then it flows more easily by dislocation climb. Although the work hardening obtained from JMatPro is more rapid than shown by experiment, the agreement with creep controlled behavior is very good.

On the other hand, there are some reservations about comparing the flow stress at 850˚C for the simple fact that it is in a temperature range where rapid gamma precipitation may occur. The results depend on the prior condition of the alloy before testing, i.e. is it quenched from the solutioning temperature or tested after ageing heat treatment. Either way, the metallurgical state of the specimen will be different and testing will produce two different results. For example, if the material is quenched from the solutioning temperature, gamma may precipitate during testing. The amount will depend on factors such as holding time before testing, and strain rate during testing, which affects how long it is held at temperature. Moreover, if the prior state alloy is in the heat treated condition, significant coarsening of the gamma is likely to occur during testing, which will cause it to soften as a function of time. The flow stress of the alloy at 850˚C, and also to certain extent at 900˚C, will therefore be history dependent and any calculated or experimental result should be used with caution.

JMatPro data was additionally compared with data available elsewhere [4], see Fig. 1c. Most of the times, agreement is very good. However, available experimental data show some inconsistencies. For example, in some cases detailed analysis shows negative values for strain rate dependence, i.e. corresponding to intersection between curves. Discrepancies among experimental data are due to the fact that the thermomechanical history of the samples is widely different. Medeiros at al [4] presents a detailed matrix of the conditions used for different researchers. Therefore, although the model used in JMatPro to predict flow stress data is not perfect, it is considered that the approximations are realistic and avoid some incoherencies observed in experimental data. Based on this, it was decided to use JMatPro flow stress data in the calculations presented in this work.



(a) (b) (c)

FIGURE 1. True stress-true strain curves from JMatPro and compression of Pyromet 718 at (a) 850˚C, (b) 1100˚C, and (c) strain rate of 0.01/s

[1] Pyromet is trademark of Carpenter Technology Corporation.
[2] JMatPro is a trademark of Sente Software Ltd

Modeling of Recrystallization and Grain Growth

Development of the Recrystallization Model and Integration into a Finite Element Model

Microstructure change during the hot working of Pyromet 718 is mainly controlled by the recrystallization as well as grain growth. Based on the experimental data obtained from compression tests and isothermal heat treatment, dynamic recrystallization and grain growth models of Pyromet 718 were established. Classical recrystallization and grain growth theories serve as the foundation of the recrystallization model implemented into the finite element code FORGE2009[3] [5]. These classical theories utilize rate equations to describe microstructure evolution through grain growth, and dynamic, metadynamic, and static recrystallization. Equation and material constants all three forms of recrystallization were extracted from literature [6, 7, 8]; and for conciseness are not presented here. The recrystallization model was integrated as user variable Fortran subroutine into FORGE2009.

Testing and validation of the recrystallization model was carried out by comparing with results available in the open literature [6, 7], and with results obtained from in house laboratory and industrial size trials, which are explained in subsequent sections.

Modeling of Surface Cracking in Hot Bar Rolling

Development of the Instability Map of Pyromet 718

In cold working processes, there are several ductile fracture criteria. Cockcroft-Latham (CL) and plastic work are widely used for predicting the location and propagation of possible defects. The CL criterion integrates the first principal stress with respect to effective strain. The effective plastic work is represented as integration of effective stress with respect to effective strain. Direction of stress is a critical factor for crack initiation in the CL criterion. On the other hand, the amount of energy is more important than direction of the stress in hot working processes because many metallurgical phenomena, like recrystallization, are involved to dissipate the accumulated deformation energy. The plastic work criterion represents the amount of deformation energy. The effective stress is a function of temperature, strain, strain rate and microstructure and it changes when a metallurgical phenomena takes place. For example, the total amount of deformation energy can be decreased when recrystallization occurs. Another important mechanism of dissipation energy is flow instability such cracks, shear bands and surface defects.

The specific plastic work was selected as a criterion to estimate the flow instability of the material under hot shape rolling conditions. The fundamentals are proposed by Lee et al. [9]. Equation (1) describes the model.

$$C_1 = \int \bar{\sigma}\left(\bar{\varepsilon}, \dot{\bar{\varepsilon}}, T\right) d\bar{\varepsilon} \tag{1}$$

In according to this approach the limiting value C_1 should be determined by coupling the local plastic work per unit volume accumulated with the surface irregularity obtained from testing, depending on the strain and temperature. If the accumulated specific plastic work is bigger than the critical value C_1, then the unstable flow might happen during the metalworking process according to this criterion.

The specific plastic work for each temperature, strain, and strain rate values were calculated from flow stress plots by calculating the area under the curve. Data used was that obtained by JMatPro. The specific plastic work values were calculated for different strain levels ranging from 0.6 to 3. Fig. 2 shows examples for strain 0.8, 2 and 3; the contour levels indicate the specific plastic work C_1, units are Nm/m^3. As expected, the specific plastic work value for Pyromet 718 is larger at low temperature and high strain rate because of higher values of the flow stress.

Determination of the Critical Value

The flow instability areas are differentiated by inspecting the surface defects and formation of shear bands in the testing specimens. Based on these observations, the critical value was decided to be 450 Nm/m^3, which was based on surface irregularity and flow instability of shear deformation. It was observed that a lower temperatures and

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[3] FORGE2009 is a trademark of TRANSVALOR.

higher strain rates the quality of the surface tends to be poor. This poor quality surface can be explained in terms of energy dissipation. To keep equilibrium the material under deformation has to dissipate energy in some ways. When deformation conditions are such that recrystallization occurs, deformation energy mostly dissipates by microstructural changes. However, if recrystallization does not occur, deformation energy is dissipated by creating extra surface, for example. Fig. 2 shows the instability map for Pyromet 718 for various strain values. In the plots, contour levels indicate the specific plastic work C_1 and the hatched area represents the unstable area.

Modeling of Porosity Consolidation in Hot Bar Rolling

Methods of Modeling Porosity Evolution

There are two methods to simulate the porosity evolution during a forming operation: modeling of the variation of the geometry of the porosity. In this case the volume variation of the porosity is tracked during the forming operation. The second method is the use of a model which allows predicting the size evolution of the porosity during the process. The first method appears to be practical, however there are some disadvantages. If a precise calculation is needed, a very fine mesh is needed to represent the porosities and that induces very long computation time. Another disadvantage is that new computations must be done if new statistical positions for the initial porosities want to be considered.

In order to reduce computation time and to predict the evolution of porosity in the whole part, a model of porosity evolution has been considered [5]. This model considers the evolution of the volume of porosity compared with the initial volume of the porosities. During the simulation, the relationship between the volume of the current porosity and the initial volume of the porosity is tracked. Equation (2) describes the model.

$$\frac{\partial \delta}{\partial t} = K_c \cdot \frac{P}{\overline{\sigma}} \cdot \dot{\overline{\varepsilon}} \qquad if \;\; p > 0 \text{, and} \qquad \frac{\partial \delta}{\partial t} = K_t \cdot \frac{P}{\overline{\sigma}} \cdot \dot{\overline{\varepsilon}} \qquad if \;\; p < 0 \tag{2}$$

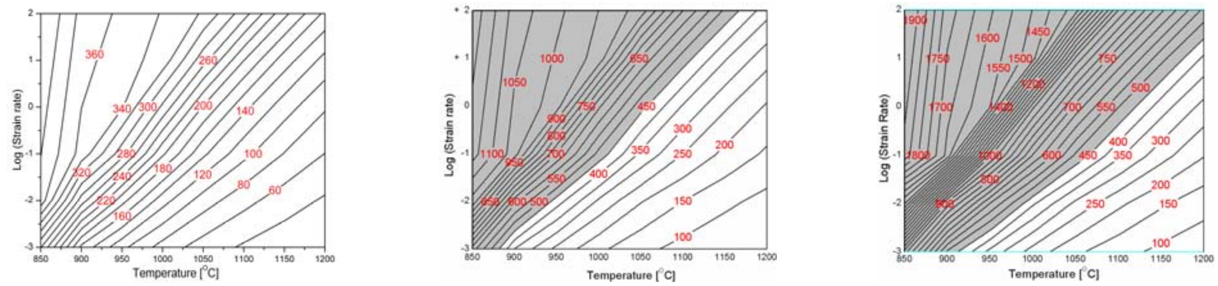
In the above equation, δ is the relative porosity volume (initial values is 1), p is pressure, $\overline{\sigma}$ is the effective stress, $\dot{\overline{\varepsilon}}$ is the strain rate. The parameter K_c and K_t in the model are for compression and tension, respectively. These values were obtained through “numerical trials”. A cylindrical billet with small spherical porosity was meshed and then a series of calculations with different stress states were run. From the results, the values for K_c and K_t were obtained. In the model it is assumed that initial cavity is spherical, the porosity ratio is very low, and that there is no anisotropic effect due to the deformation of the cavity. This model is implemented in FORGE2009.

APPLICATION TO INDUSTRIAL PROCESSES

Ingot Conversion Process

To demonstrate the capability of the present model, the complete Pyromet 718 conversion process was simulated using FORGE2009. The process includes several upsetting and drawing operations with reheating in between. One operation itself includes several passes, and one pass includes several blows. The entire process results in hundreds of forging and heat transfer operations. The simulation is fully coupled and includes the calculation of mechanical, thermal, and evolution of grain size variables. Initial ingot size is 508 mm round, initial temperature is 1175°C, initial grain size varies from 500-1000 μm, tooling temperature is variable, friction factor is 0.7, heat transfer coefficient with air is 10 W/m^2/°C, and heat transfer coefficient between workpiece and tooling is 2000 W/m^2/°C.

Figure 3 shows results for the upsetting operation. Results are shown in terms of effective strain, dynamically recrystallized volume fraction X_{DRX}, and average grain size. Distribution of this variables shows that the process is rather inhomogeneous, i.e. “dead zones” are developed at both ends of the ingot. The pattern distribution is consistent with industrial observation, and can be used as starting point to modify the upsetting process aiming to minimize the volume of the dead zone, which translates into higher ingot yield.

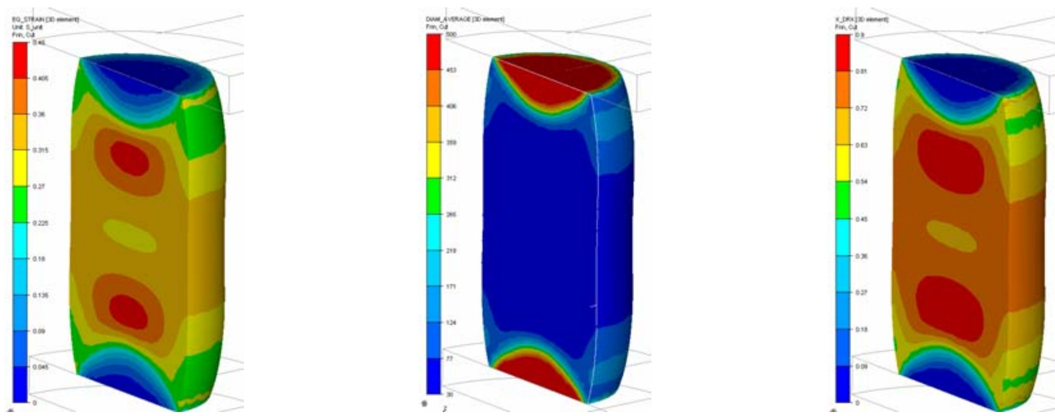


(a) (b) (c)

FIGURE 2. Instability map in terms of specific plastic work of Pyromet™ 718. (a) strain 0.8, (b) strain 2, (c) strain 3

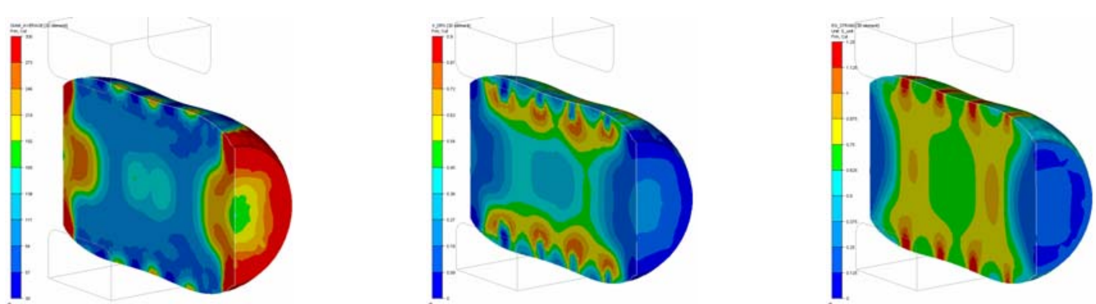
In order to keep track of all the variables throughout the complete conversion process, they were carried over from operation to operation up to end. Fig. 4 shows results at an intermediate pass of the drawing operation following the first upsetting. Results are average grain size, accumulated effective strain, fraction of recrystallization. It is clearly seen how the "dead zones" at the ends of the ingot start getting smaller due to the side pressing. Moreover, a number of "dead zones" are developed near the surface due to the friction at the die-ingot interface. These distribution patterns are very useful in designing the operation sequence and parameters for an optimum conversion process.

Figure 5 shows the (a) calculated average grain size for an operation previous to swaging. The initial geometry is octagonal in cross section and is forged down into a double octagon. The center shows fully recrystallized microstructure, however, close to the surface the structure is necklace type where the recrystallized grains are nucleating at the unrecrystallized grain boundaries. The last condition represents a quality problem. Therefore, modeling of the grain size evolution represents a powerful tool to design more robust processes, which main objective is to produce appropriate final grain size by modifying tool geometry, and processing sequence.



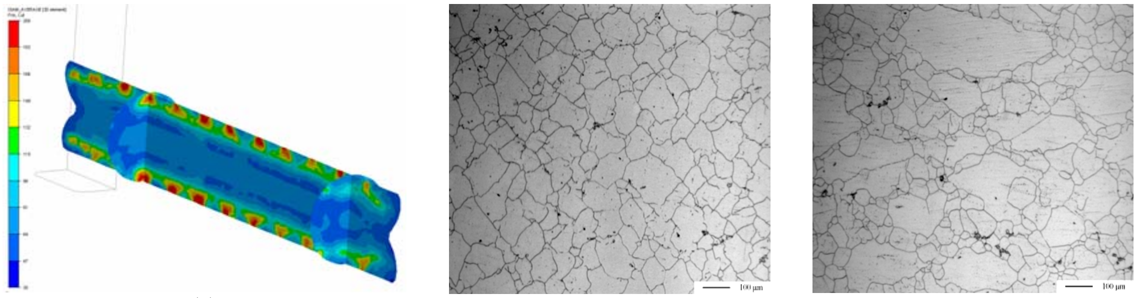
(a) (b) (c)

FIGURE 3. Simulated results of the upsetting operation in Pyromet 718 conversion process: (a) effective strain, (b) average grain size, and (c) dynamically recrystallized volume fraction X_{DRX}.



(a) (b) (c)

FIGURE 4. Results for the drawing operation after first upsetting in Pyromet 718 conversion process: (a) average grain size, (b) dynamically recrystallized fraction X_{DRX}, and (c) accumulated effective strain.



(a) (b) (c)

FIGURE 5. Results for the second to the last operation in Pyromet 718 conversion process: (a) Calculated average grain size, (b) microstructure at the center of the billet, and (c) close to the surface.

Wrinkles and Surface Cracks in Hot Bar Rolling

The plastic work approach was implemented into FORGE2009. Application consists in investigating the cause of wrinkles and cracks obtained in the reverse rolling of Pyromet 718. Initial billet size is 203 mm round and final geometry is 102 mm square. The reverse rolling schedule consists in several passes that includes: flat, box, and oval passes. Simulation conditions are: constant shear fraction factor of 0.65, heat transfer coefficient at the interface between billet and rolls of 2000 W/m^2/°C, and rolls and environmental temperature were 200 ºC and 25ºC, respectively. Results in terms of specific plastic work are shown in Fig. 6.

These simulations show that instability resulted from pass 8 might cause the surface cracks in the final geometry. Since the instability was accumulated in every pass, it was necessary to reduce the instability wherever a change can be implemented based on equipment and process constraints. It was observed that a significant increment in specific plastic work at the edge of the oval in Pass 7 might cause the formation of wrinkles. Uneven deformation from center to edge in the oval pass gives differential elongation which leads to surface defects resulting from the shear forces set up. In the present work, the objective was focused on improvement of the roll pass design to reduce the possible surface defects.

In this study, geometry of the rolls was kept constant, and the only variables were the number of passes and roll gap. Fig. 7 shows the simulation results of the new schedule; note that there is one oval pass less. It is observed that there was a reduction of instability for the improved roll pass design compared to the original roll design. However, this reduction of instability was not to a great extent.

Figure 8 shows comparison between the simulated and actual geometry of the final upper vertical corner. For the original pass schedule, Fig. 8a, the simulation accurately predicts that the roll groove remains unfilled, and that the maximum plastic specific work corresponds with the location of wrinkles and cracks. On the other hand, Figure 8b shows that the modified schedule leads to a complete filled roll groove and that cracking is much less, which corresponds to a lower specific plastic work.

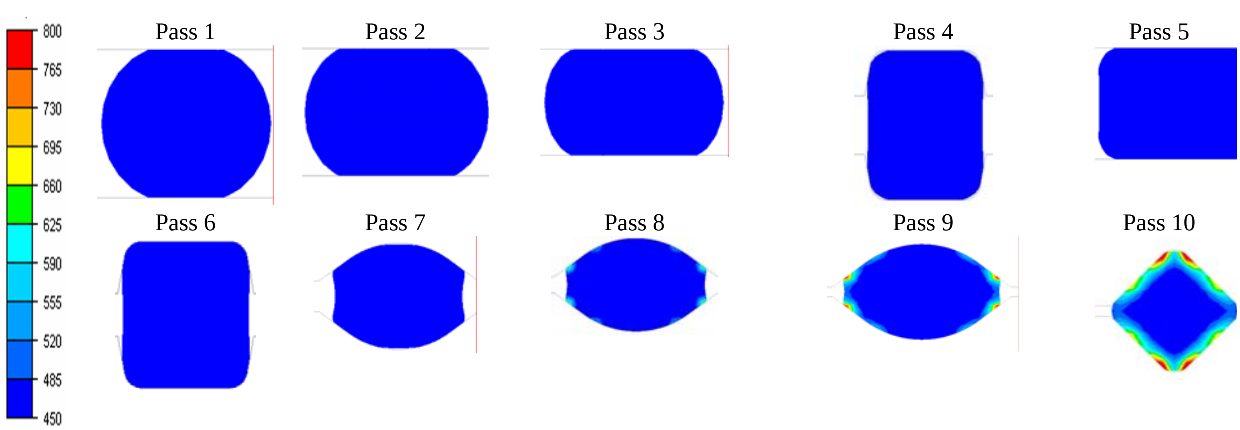


FIGURE 6. Accumulated specific plastic work of the original Pyromet 718 rolling schedule.

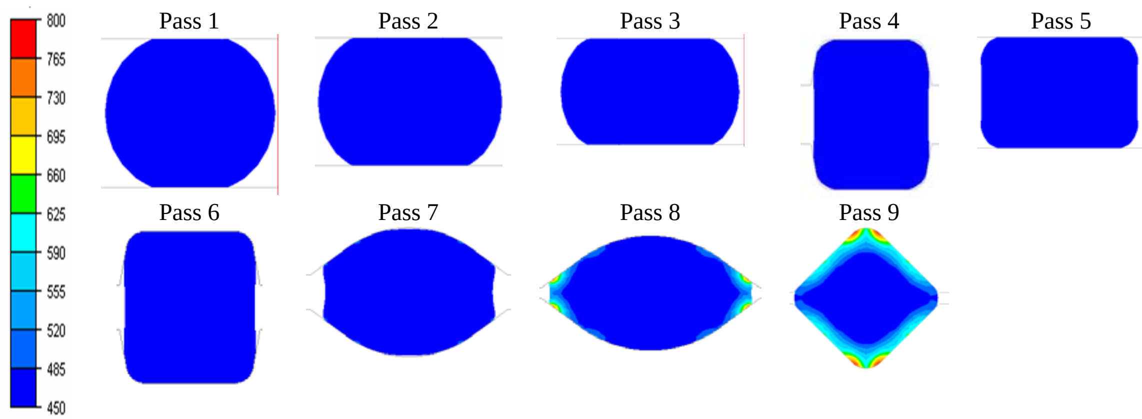
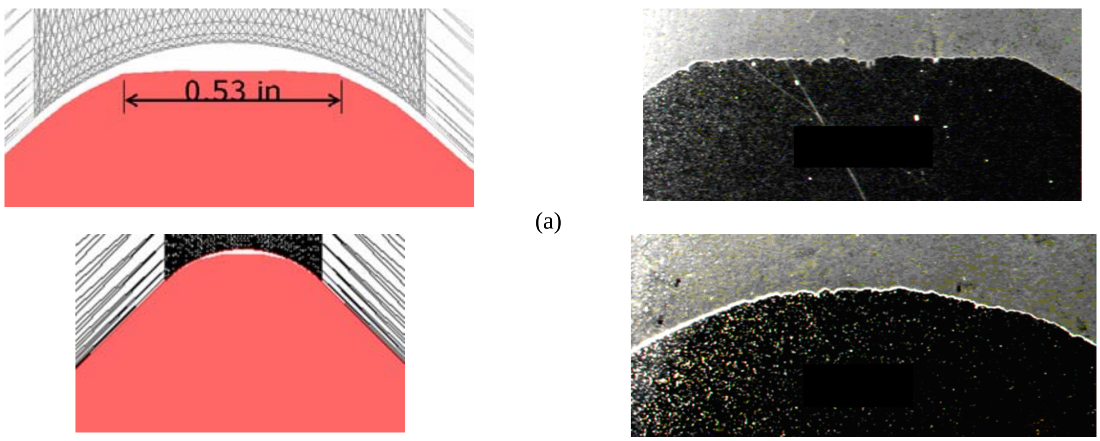


FIGURE 7. Accumulated specific plastic work of the modified Pyromet 718 rolling schedule.



(b)

FIGURE 8. Defects and roll groove filling at last pass. (a) Original pass schedule and (b) Modified pass schedule.

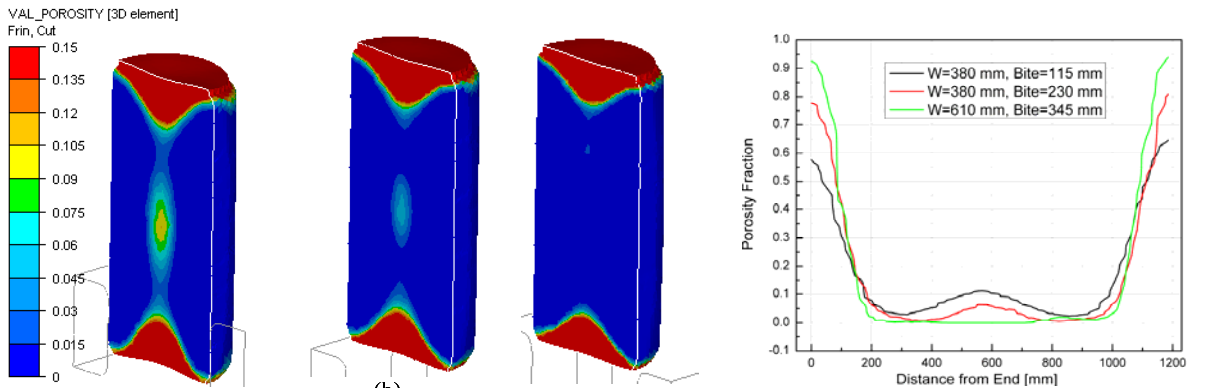
Porosity Evolution in Ingot Conversion and Hot Bar Rolling

Ingot conversion was the process chosen to test the proposed porosity evolution model. A pass schedule for a 508 mm round ingot was simulated using three different process conditions. First condition is 380 mm die width and 115 mm bite size, second is 380 mm die width and 230 mm bite size, and the third one is 610 mm die width and 345 mm bite size. Results of the relative porosity volume after upsetting plus one drawing operation are shown in Fig. 9. In addition, plots of the same variable from end to end along the centerline are shown in Fig. 10d. The effect of the process variables on the porosity evolution can be clearly seen. Better cavity consolidation is observed as bite size and tool width increases. This model can be used to run a parametric study to find out the optimum conditions for a given alloy and process.

Further evaluation and validation of the porosity evolution model was carried out by simulating the continuous rolling process of a 17-4PH stainless steel, where the initial geometry is a 104 mm square down to a 78 mm round. Fig. 10 shows the initial actual porosity level of the workpiece to be rolled and the resulting porosity obtained with the original pass schedule. The roll pass design was optimized by calculating the effect of geometry of the rolls on the porosity evolution. The plot in Fig. 10d shows the evolution of the relative porosity volume; it can be seen how the value at the end of the rolling process is zero, which means full consolidation of the porosity. Fig. 10e shows the actual porosity level obtained by the optimized rolling schedule. The material is fully consolidated.

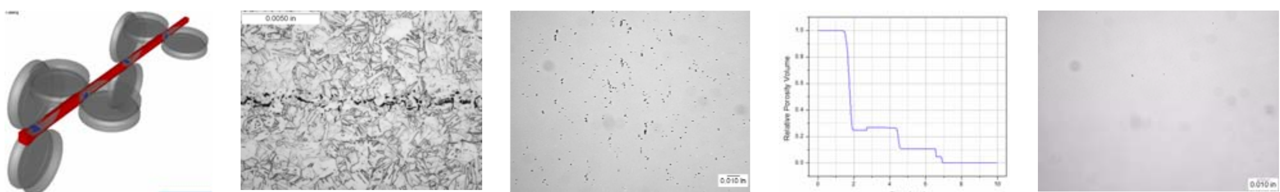
CONCLUSIONS

Numerical modeling has been presented to simulate the evolution of grain size, surface defects and porosity during hot metal working processing. Mathematical models implemented into the finite element system FORGE2009 were validated by comparison to actual samples from industrial size trials.



(a) (b) (c) (d)

FIGURE 10. Simulated relative porosity volume after upsetting and one drawing operation. (a) die width=380 mm, bite size = 115 mm, (b) die width=380 mm, bite size = 230 mm, c) die width=610 mm, bite size = 345 mm and (d) relative porosity volume along the centerline.



(a) (b) (c) (d) (e)

FIGURE 11. (a) Model of the 4-Passes rolling schedule, (b) actual porosity along the center line of the initial billet, (c) actual unconsolidated porosity obtained from original rolling schedule, (d) calculated evolution of the relative porosity volume along the center line for the optimized rolling schedule, and (e) actual porosity at the center line obtained by the optimized rolling schedule.

The microstructural model has been demonstrated to be effective in predicting the microstructure observed. A coarser recrystallized grain structure is predicted at the centre of the ingot. Also, the process model accurately predicts the "dead zone" immediately below the die/ingot interface and extending someway into the cross section.

Wrinkles and surface cracks was another topic studied. A numerical model based on the specific plastic work approach was applied in hot shape rolling simulation. The model accurately predicts the location and extension of such defects in the process.

Also, a new porosity evolution model was applied to cogging and hot rolling to predict the porosity consolidation. This new approach avoids excessive computation time and allows tracking porosity evolution at any location in the workpiece.

In all the studied cases, the results were then used to derive new schedules and process parameters where the level of a given thermo-mechanical variable was more affective to achieve the high level of quality required in high performance applications.

Finally, this work clearly demonstrates that modeling tools are mature enough to be routinely used for process improvement.

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