Light Metals 2015
Edited by: Margaret Hyland
TMS (The Minerals, Metals & Materials Society), 2015

OPTIMIZATION OF ISOTHERMAL HOT ROLLING PARAMETERS USING ANSYS AND LS-DYNA

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Keywords: A359, hot rolling, Al-MMC, aluminum, ANSYS

Abstract

Manufacturers of rolled materials are always striving to reduce the costs associated with production—be they time, material, or waste. This is especially true with the manufacture of next-generation particle-reinforced materials, such as those used in high-value automotive components. Process variables such as temperature, roller speed, and plate dimensions, among others, all affect strength, ductility, and anisotropy of the hot rolled plate. Manipulation of the thermo-mechanical processing (TMP) parameters can help to optimize mechanical properties, which would reduce waste and improve quality. A parametric study was conducted via ANSYS and LS-DYNA to numerically simulate symmetric hot rolling. The TMP parameters have been varied to characterize how geometric and material properties confer a mechanical response for single-pass isothermal rolling. This approach to virtual processing represents a means by which manufacturers can lower the time, material, and scrap costs associated with developing new, high-value components. Conditions that minimize edge cracking as predicted by a ductility model are presented.

Introduction

Aluminum metal-matrix composites (Al-MMCs) are an important area of study for high-strength components. This study focuses on the properties of aluminum alloy A359 with 30wt% SiC particle reinforcement, a composite structure that confers high strength to low density components. The addition gives this material increased strength, comparable to steel, while maintaining its light weight. However, the additive also decreases the aluminum's ductility, making it difficult to machine. The material is typically cast to 300 x 300 x 25 mm plates and then rolled to the desired thickness. The reduced ductility from the SiC leads to edge cracks, which requires the edges to be trimmed, thus increasing waste and machining costs. Review of literature reveals investigations into the temperature distribution in hot rolled sheets, the strain rate as a function of rolling geometry, and the effects of variation in arc of contact. While these results are valuable, they require further calculation to be relevant in the prevention of edge cracks. The present work attempts to characterize the effects of the rolling geometry on the inelastic response in Al-MMC sheets rolled at 538°C, with the aim of predicting the extent of edge cracks for a given geometry and optimizing the rolling process at this temperature.

Relevant Literature

Hot rolling has been a topic of interest to engineers for many years, and as such extensive literature exists on the subject. Research tends to focus on the temperature distribution throughout the work piece, and is typically specific to steels. Other papers have introduced the metallographic causes of edge crack initiation, including grain structure and unwanted metallic precipitates in certain susceptible alloys. One work of interest [1] presented an extensive examination of spread in rolled sheets, which can be correlated to edge cracking. Clearly a wealth of information is available to manufacturers regarding various aspects of the rolling process and the causes of edge cracks; the present study attempts to bridge the gap between academic knowledge and industry practice by directly predicting edge cracking based on evidence from finite element analysis.

Material Characterization

Previous researchers [2] used tension and torsion testing in order to characterize this particular MMC at temperatures ranging from room temperature to 538°C. From these results it is clear that commonplace variations in the microstructure can have a severe negative impact on material properties: a cluster of SiC particles produces a stress concentration, while an area of reduced SiC content lacks the strength of the composite material. Still, there are noticeable trends: at low strain rates, toughness consistently decreases with temperature. With higher strain rates, this holds true until approximately half the melting temperature, at which point toughness begins to increase with temperature. This work assumes continuum material properties based on a conservative interpretation of the results from [2], reserving more complex microstructural effects for future work. The behavior of the material is approximated using a power law plasticity (PLAW) model of the form:

$$\sigma_Y = K\varepsilon^m \dot{\varepsilon}^n \tag{1}$$

Here σ_Y is the equivalent yield stress, ε is the equivalent plastic strain, and $\dot{\varepsilon}$ is the equivalent strain rate. K, m, and n are material constants that were determined using Eureka, a robust curve-fitting software. Both m and n are independent of temperature, having values of 0.1784 and $1.984*10^{-5}$, respectively. K controls the thermal sensitivity, and takes the form:

$$K = 850.6*10^6*T^{-0.115} \tag{2}$$

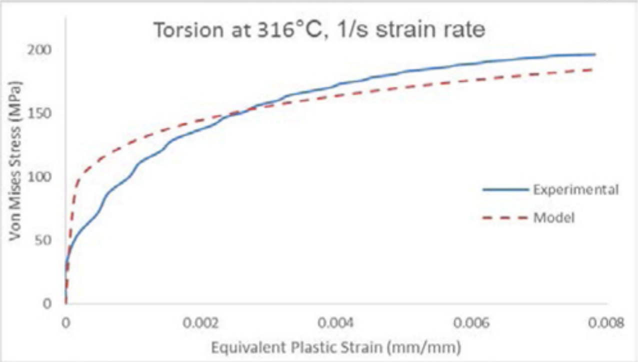

Figure 1: A comparison of the material model to the experimental data at 316 C and strain rate of 1/s. It is difficult to predict the behavior of MMC's, as minute processing defects can lead to pronounced variability in specimen behavior.

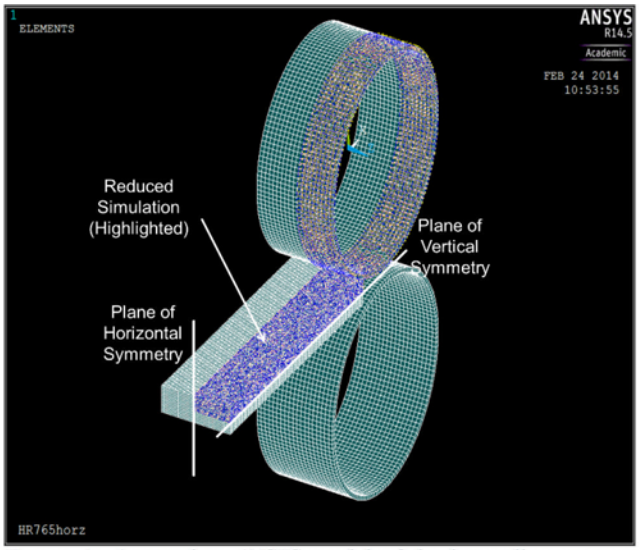

Figure 2: A complete ANSYS model of the hot rolling process. During this study, the two planes of symmetry were used to reduce the model to one fourth of the size pictured.

With temperature T in Kelvin. This approximation achieves similar toughness, slightly underestimates fracture stress at the temperatures under study, and fits the curve of the experiment data with a goodness of $R^2 \geq 0.9$.

Numerical Approach

Finite element analysis (FEA) was used to characterize the effects of the thermo-mechanical processing parameters (TMPs) under examination. FEA uses nodes and elements to numerically simulate mechanical behavior. Analysis of FEA results reduces the need for material samples and destructive testing. Using the ANSYS modeling program, an input file was created that would simulate isothermal hot rolling at 25°C, 316°C, and 538°C. A parametric approach was carried out to produce an optimal hot rolling configuration. The model consists of three structures: the roller, the plate, and the feeder. The feeder serves to push the plate into the roll bite at the beginning of the simulation. The plate and roller are composed of 8-node solid brick elements, and the feeder is composed of rigid shell elements. The roller is modeled as hollow and rigid to reduce simulation time. However, this also prevents an accurate depiction of roller deformation. Although in industrial practice deformation will occur in the roller, this model assumes negligible roller deformation. The entire model is comprised of 300,000 nodes and 230,000 elements. To reduce the size of the simulation, only one quarter of the rolling operation is modeled. Because hot rolling is symmetric in two directions, no information is lost by this simplification. The mesh on the plate is varied so as to concentrate the finest elements on the surfaces, as opposed to the bulk material. This allows for very accurate material modeling in the areas of interest while keeping the overall simulation time to a minimum. Once the chosen geometry is created, ANSYS proceeds to simulate the rolling process using the LS-DYNA solver. The stress and strain histories for any node or element can easily be retrieved, but this study focuses on the residual values in a single cross-section of the plate, such as the Cockcroft-Latham damage parameter. This cross-section is in the plane perpendicular to the roll direction and centered along the length of the plate. The lengthwise center was chosen to avoid possible entry- and exit-effects at the ends of the plate. The effects of variation in six parameters are studied: roller diameter, percent reduction in thickness, temperature, roll speed, static friction coefficient, and dynamic friction coefficient. The variable friction coefficients are intended to represent different states of lubrication. These six parameters were varied in a Taguchi L18 parametric array, which uses an orthogonal array of parametric variables to reduce the number of simulations required. For each parameter, three levels were chosen, representing a "high", "medium", and "low" value within acceptable variation of that parameter. Each level for a given factor was used in six of the eighteen tests, and paired with each level of each other factor in an equal number of tests. The result of this orthogonal array structure is that, when the outputs from the six tests at a given factor level are averaged, the results should be independent of the other factors.

Parameter	High	Medium	Low
Roller Diameter (mm)	600	400	200
Thickness Reduction	75%	50%	25%
Temperature (°C)	538	316	25
Roll Speed (m/s)	1.5	1.0	0.5
Static Friction	0.9	0.6	0.3
Dynamic Friction	0.9	0.6	0.3

Table 1: The six parameters under study and their levels. 538°C is 90% of the melting temperature of the A359 matrix.

Discussion

Unsurprisingly, percent reduction has a profound effect on the post-processing characteristics of the plate. Specifically, the ratio between the average Von Mises equivalent stress at the edge of the plate to that at the width-center tripled between the low and high levels for this parameter. This means that at high percent reduction, the edge of the plate experiences three times the stress at the center, which is a clear indicator of potential edge cracks. Likewise, the edge-to-center ratio doubled (from 0.58 to 1.18) for residual spreading strains between the low and high reductions.

More interesting is the result of nearly no significant dependence on friction coefficients for any of the plate properties studied. This likely indicates that the friction coefficients alone are not enough to simulate variation in lubrication properties.

Roller diameter and percent reduction were found to have approximately equal influence on the residual spreading stresses. These two factors determine the length of contact between roller and plate, which is known to play a factor in spread. Larger roller diameters were shown to decrease the roll-direction residual stresses, as well as increase the depth (from the plate surface) that the maximum roll-direction stress occurred.

Increasing temperature appeared to reduce the percent of plate cross-sectional area that reached a critical threshold of Cockroft-Latham damage. However, when the damage threshold was varied to account for temperature dependence in the material, this effect disappeared.

Conclusion

The simulations provide a means for predicting the characteristics of rolled plates without any waste in material. Directional stress and strain histories allow experimenters and manufacturers to use a tensile load frame to recreate a specific section of plate for further study. Furthermore, parametric study has shown the effects of single-parameter variation, allowing users to calibrate the rolled characteristics of a sheet to fit their needs. Once trends in the data have been further studied and secondary tests completed, precise equations could be written to calculate strains throughout the plate based on known quantities. Already steps have been made towards parameter interactions, although with the current data set these estimates are not very precise. With further work, this system of simulation analysis can be developed into a powerful tool to assist both researchers and manufacturers. Temperature- and strain rate-dependence of the material model may need to be modified to better capture the material behavior.

References

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