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Experimental Analysis of Velocity Fields in Hot Extrusion of Aluminium Alloy 6351

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Abstract. Hot extrusion is a metal forming process with a huge importance in the manufacturing of long metallic bars with complex shapes, and because of this, academics and industries are especially interested in better understanding how metal flows during the process. In order to have a reliable computational tool that can help to solve and to obtain material internal flow, experimental tests and numerical simulation with the finite element method were carried out to obtain results of the velocity fields generated in hot direct extrusion of aluminum billets (aluminum alloy 6351). The experimental results of the velocity field will be used to validate a computational code based on the finite volume method.

Introduction

Hot extrusion is a metal forming process with a huge importance in the manufacturing of long metallic bars with complex shapes, and because of this, academics and industries are especially interested in better understanding how metal flows during the process.

In order to have a reliable computational tool that can help to solve and to obtain material internal flow, experimental tests have been carried to obtain results of the velocity fields generated in hot direct extrusion of aluminum billets to preview dead zones and flow instabilities and misorientation.

The traditional “scratched grid pattern technique” [1], using split billets is very difficult to visualize regions with large deformation, as in shear zones or at the upper layers where the grid lines have the tendency to get erased and, therefore, some errors are done in the analysis of the experimental results.

Plasticine has been used as a modeling material for more than fifty years to evaluate flow behavior of metals as observed in metal forming processes [2], as well as visioplasticity [3,4]. Wang et al. [5] proposed another visioplasticity method based on color-patterning image processing. Both methods can only provide qualitative data because the model material cannot reproduce the viscoplastic properties of the actual extruded materials, and therefore these method are not completely adequate.

To better visualize the metal flow, Valberg [6] presented the technique known as “stripe pattern grid technique” with contrast pins inserted axially and radially in the longitudinal symmetry plane of the billet as illustrated by Fig. 1(a).

This method also presents experimental difficulties related to the manufacturing of the split die, necessary to remove the extruded billet without damaging it, and to prepare the surfaces to be analyzed, since the billet has to be cut off at its longitudinal section and then polished and etched to reveal the flow pattern. Finally, if the flow is to be evaluated during extrusion, many billets have to be deformed and prepared.

An alternative method to visualize material flow during the process is the numerical simulation with the finite element method by models representing the billet with the contrast pins. The pins are necessary because the simulation results of flow velocities are not directly available to input in the method of Valberg.

In this work the "stripe pattern" method was used to analyze the extrusion of aluminum alloy 6351 with contrast pins made with the aluminum alloy 2011. The same process was also simulated by the finite element method which results were validated with the experimental results.

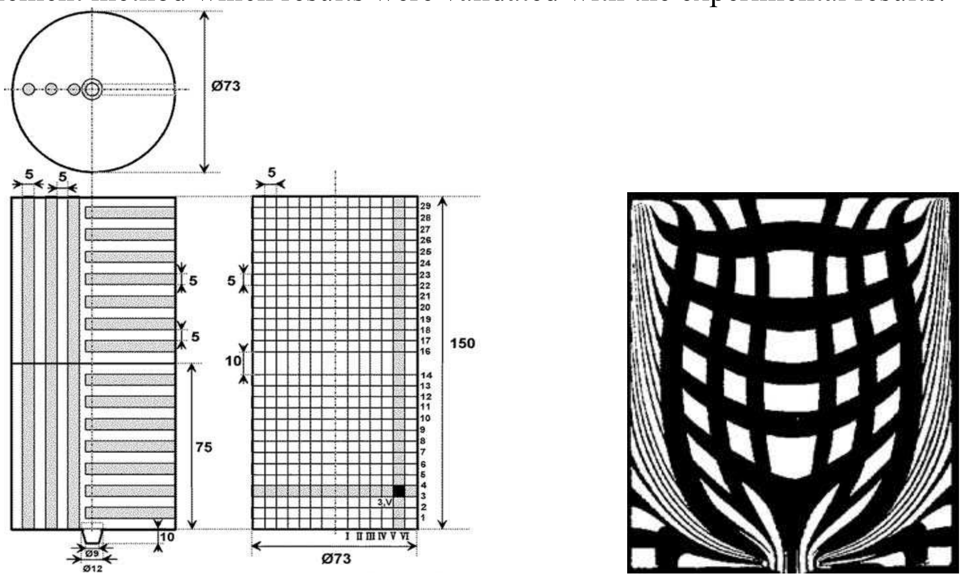


Figure 1. Two steps of the "stripe pattern grid technique": (a) The pins positioned inside the billet before extrusion, and (b) the metal flow profile after extrusion [6].

Materials and Methods

Experimental Analysis. Fig. 2 shows the tooling set up used in the experimental tests. The extrusion die presents the following dimensions: inlet diameter of 60 mm; outlet diameter of 20 mm; work angle of 32.3^{o} corresponding to a area reduction of 89%.

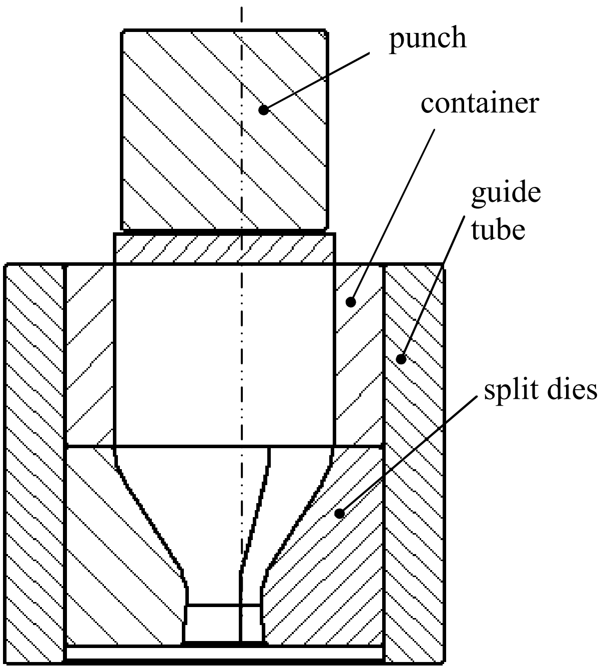


Figure 2. Extrusion tooling

Billets with 58 mm in diameter and 40 mm long were cut off from an aluminum 6351 T5 bar and machined to receive the contrast pins with 5 mm in diameter made with aluminum 2011, three longitudinal and four radial, as shown in Fig. 3. After machined the workpieces were solubilized at 515 ^{o}C for 60 minutes and air cooled.

Extrusion tests were carried out in a hydraulic press with a speed of 10 mm/s. Before the tests, the dies were lubricated with an mixture with mineral oil, graphite and molybdenum disulphide. The workpieces were heated at 450 ^{o}C for 30 minutes and the tools were heated at 200 ^{o}C to minimize the heat transfer and workpiece cooling.

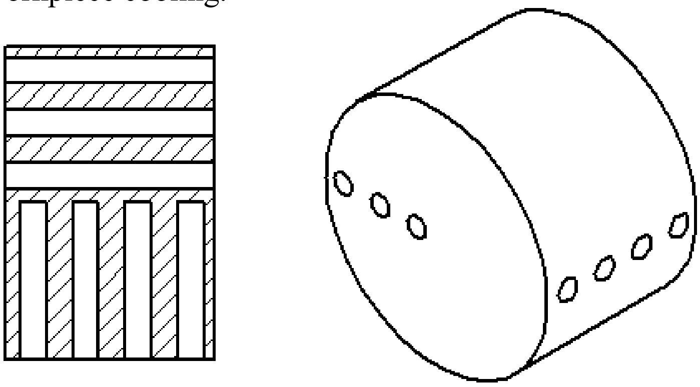


Figure 3. Billet: section and isometric views showing the holes for the contrast pins

Extruded workpieces were removed from the container, air cooled and cut off at the medium longitudinal plane, then milled, polished and etched with a reagent (solution of 85 ml $H_2 0$, 15 ml HF and 15 ml HNO_3) to reveal the patterns shown in Fig. 5.

Numerical Simulation. The software Forge 2008 [7] based on the finite element method was used to simulate the process with the same conditions applied in the experimental tests. This software present an interesting feature that is the possibility of simulating up to fifteen objects as workpieces, making possible to analyze the flow of the billet together with the contrast pins.

The billet and the contrast pins were modeled with tetrahedral elements with constant size of 2 mm (Fig. 4). Table 1 presents the coefficients used to model the billet and pins materials with the Hansel-Spittel law [8]. The tools were modeled as rigid. The viscoplastic friction model was adopted with the friction coefficient equal to 0.5.

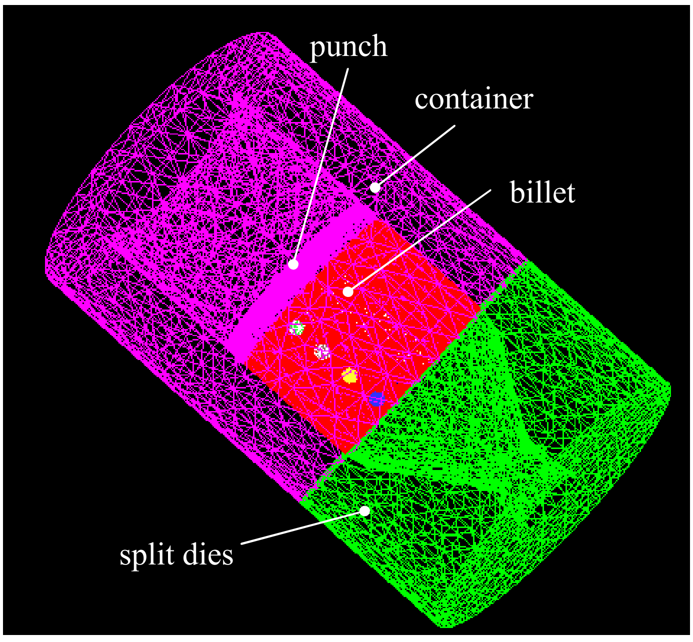


Figure 4. Finite element model of the extrusion tooling and billet with contrast pins

Table 1 – Hansel-Spittel law coefficients used to model the flow stress of aluminum alloys

Material	Coefficients				
	A1	m1	m2	m3	m4
AA 2011	667.98713	-0.00485	-0.03347	0.08079	-0.00228
AA 6351	953.65542	-0.00524	-0.01407	0.10998	-0.00913

Results and Discussion

Fig. 5(a) and (b) show the patterns formed after reducing the billet length to 20 and 10 mm respectively. It can be observed that the pins are easily viewed and therefore 2011 is a good contrast material to 6351 aluminum alloy.

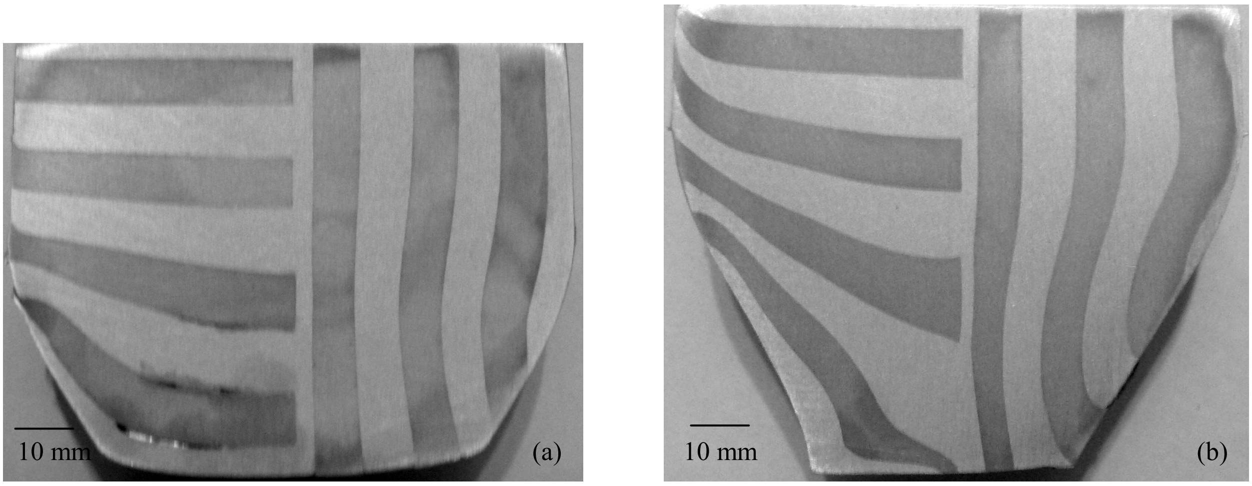
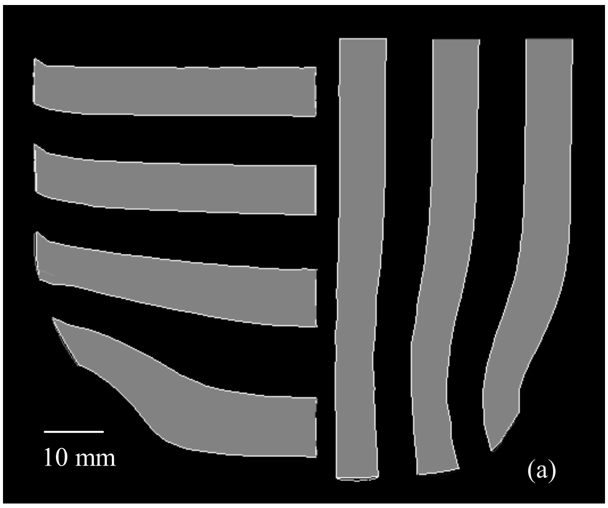


Figure 5. Experimental patterns of contrast pins after extrusion – (a) 20 mm billet length (b) 10 mm billet length.

These patterns should be compared to correspondent patterns obtained by numerical simulation and shown in Fig. 6(a) and (b) for the same billet lengths of Fig. 5(a) and (b).



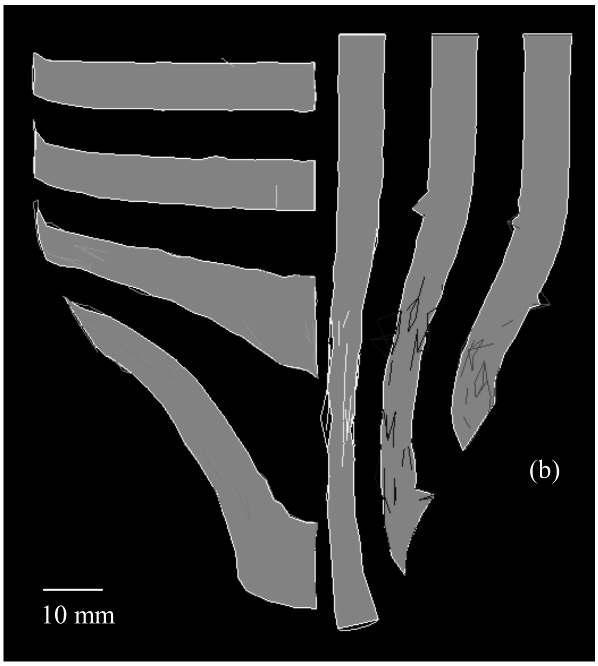


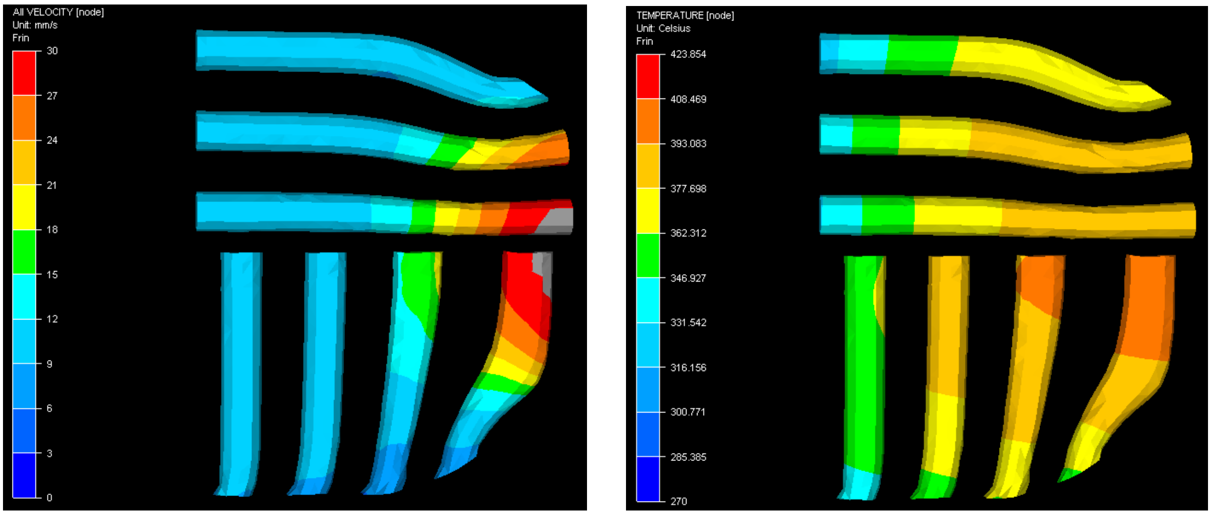
Figure 6. Simulated patterns of contrast pins after extrusion – (a) 20 mm billet length (b) 10 mm billet length.

The patterns are very similar and the differences found in each pair of figures (a) or (b) can be explained by the experimental difficulty to reveal by grinding the exact medium longitudinal section, and therefore some experimental stripes are thinner than the correspondent simulated stripes.

It can be observed in Figs. 5(b) and 6(b) that the curvature of the stripes are very similar, indicating that all the parameters chosen for the simulation, mainly friction coefficient and flow stress curves, were the very suitable to represent the actual process.

Fig. 6(b) shows some distortions in the longitudinal stripes which can be associated to the mesh size defined to the pins. Probably these distortions should not occur with smaller element sizes.

With this model it is also possible to obtain the local velocity (Fig. 7(a)) or the temperature distribution (Fig. 7(b)), results which are very difficult to measure experimentally and are very useful to the method of Valberg as well to other methods developed to calculate extrusion stresses and strains which have velocities and temperatures as inputs.



(a) (b)

Figure 7. (a) Velocity distribution, (b) temperature distribution

Conclusion

In this work the “stripe pattern” method was used to analyze the extrusion of aluminum alloy 6351 with contrast pins made with the aluminum alloy 2011. The same process was also simulated by the finite element method which results were validated with the experimental results. These results will be input in the method of Valberg to calculate the stresses and strains, and to validate a volume finite method which is being developed by these authors.

The experimental results showed that the pins are easily viewed and therefore AA 2011 is a good contrast material to 6351 aluminum alloy.

The aspect and curvature of the simulated stripes are very similar to the experimental ones, indicating that all the parameters chosen for the simulation, mainly friction coefficient and flow stress curves, were the very suitable to represent the actual process.

Some problems like the differences of thickness (experimental stripes) and distortions (simulated stripes) should be solved in future tests with more accurate grinding and choice of element size.

Acknowledgments

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