International Journal of Engineering and Management Sciences (IJEMS) Vol. 5. (2020). No. 2
DOI: 10.21791/IJEMS.2020.2.25.

Simulation of Hot Rolling by Cellular Automata

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Abstract. Our research is focusing to one of the most complex and important production step of flat rolled products that is the simulation of hot rolling. During hot rolling two phenomena as work hardening and the process of regeneration of crystals has strong influence for physical properties of microstructure of aluminium alloys. It needs to be taken into account in case of rolling technology steps and development. When we talk about aluminium the dynamic softening in fact it is dynamic recovery that is followed by dynamic recrystallization. It goes in the same order of magnitude rate. But in steels the recovery has only a minor effect. Hot rolled and newly modified grain structure is influenced by these dynamic phenomena. Hot rolled grain structure goes through significant changes under further production steps like cold rolling and heat treatments. But aside from these intermediate production steps the microstructure that we get after hot rolling has significant effect for mechanical and grains structure of the final flat rolled product. Proper technology planning is essential that for cellular automata simulation method can ensure useable and good solution for the simulation of recrystallization.

Introduction

In world wide millions of tons flat rolled aluminium sheets are produced per year for customers. For a technology engineer it is not easy task to build up a proper technology that fulfil product requirements. These requirements that we can call material properties like material thickness, grain size, mechanical properties, deep drawing capability etc. are in focus for end users and the rolled material has to achieve these specified customer requests. We are working on to find a simulation that could support industrial engineers in their daily practice to find the best optional production route. Our idea at first hand the simulation of material behaviour and not the technology itself. For the rolling technology simulation from material workability, rolling passes etc. FEM simulations are more common solutions. Cellular automata is different and it could give better solution for recrystallization simulation. Cellular automata working is easier and calculation time is shorter. This is an advantage in industrial application where time factor is important and material properties are in focus.

The simulation of grain growth and recrystallization by cellular automata method has been researched area for more than 20 years until today in Institute of Physical Metallurgy, Metalforming and Nanotechnology at University of Miskolc. At the beginning they focused on static recrystallization. Later researchers have introduced that their improved method can simulate hot rolling and dynamic recrystallization, but they focused on physical processes under annealing even so. Improved cellular automata has been simplified to 1D and they solved also the scale.

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Every automata cells have own state. According to the given mathematical algorithm these cells can calculate and based on the calculated result these can keep their state or they change it [1,2]. We can define these cellular states as rolled, recovered, recrystallized etc.. Stored energy is the mutual point of workability, recovery and recrystallization. Our automata calculates with stored energy changing and finally it identifies the actual material state as a simulation of microstructure. In our research we could connect recovery and recrystallization calculation in one automata. These were not real physical measurements. In our paper we report about further results of improvements of hot rolling 1D cellular automata simulation. We introduce the results of capability calculations. It is the main factor of our study.

1. Recovery simulation by 1D cellular automata

Automata connects 10000 cells in 1D like a chain. Every cell has two other neighbours with periodic border terms of cells. It means that the first and the last cells in the lace are connected to each other. The cell chain is unending. Automata calculates with 1000 calculation steps. With this rule our automata is proper for such a complex calculations. The following basic parameters were set for this capability study of recovery: each cell has formed state (stored energy: 1000 J/cell; critical stored energy for forming: 100 J/cell), isotherm circumstances (500°C). It can be demonstrated like a cold rolled material with height dislocation density/stored energy which is annealed.

Figure 1. presents the stored energy changing in function of automata calculation steps with using different activation energy.

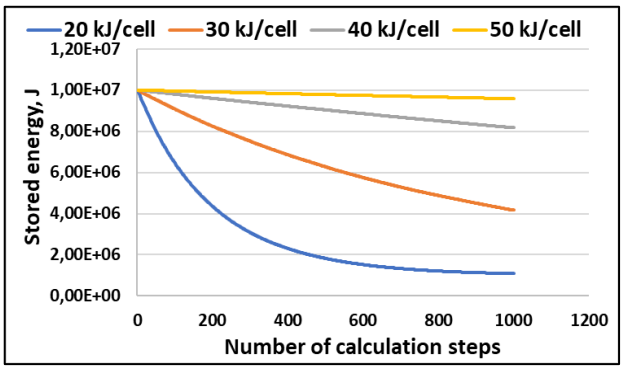

Figure 1. Stored energy changing in function of 1D cellular automata calculation steps with using different activation energy

Results show us the different value of activation energy has different effect for the stored energy. Increasing activation energy slows the recovery. The value of stored energy didn't change efficiently in case of 50 KJ/cell. In the reality we can say the dislocation density is remained height and we can't speak about significant softening mechanism. The decreasing intensity of stored energy parameter Kst=10 were chosen for calculation. Critical sored energy is an important parameter. When a cell reaches this value the cell become activated. Activated cell change own state in this case from formed state to annealed (recovery) state. The cell after activation changes the state and the stored energy of cell is decreasing. In case of Kst=10 the stored energy of cell drops the tenth of energy. This is the

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reason why lower activation energy is causing drastic drop in stored energy during calculation. Nature of 20 KJ/cell activation energy curve is exponent that is typical for recovery mechanism.

2. Connected recovery and recrystallization 1D cellular automata

Recovery and recrystallization are responsible for softening mechanism in metals [3]. Our goal was to connect recovery and recrystallization in one automata that can handle both mechanisms parallel in one calculation (1).

$$E_{st}(t+\Delta t,i) = E_{st}(t,i) - \frac{E_{st}(t,i) - E_{str}}{K_{st}} \tag{1}$$

We used almost the same basic parameters like in previous chapter for recovery. For this calculation 1500 calculation steps and different temperatures (iso and non-isothermal) were applied. Results were similar until approximately 200 number of calculation steps (Figure 2-3.). There is a drop in stored energy. This is the point where recovery is followed by recrystallization. Over 200 calculation steps curves start to separate from each other and there is big difference in stored energy. Stored energy didn't change significantly at 300°C. This was a low temperature for recrystallization but recovery was responsible for softening. We got the lowest stored energy at 500°C and the recrystallization fracture is almost 0,9 after calculation. This is a typical curve of Avrami phase transformation. In the reality there are non-isothermal cooling therefore we simulated this case also. Orange curve represent this opportunity where starting temperature was 500°C and at every calculation step it was decreased by 0,2°C. Recrystallization started but it wasn't finished. These results demonstrate that our automata can differentiate these recovery and recrystallization.

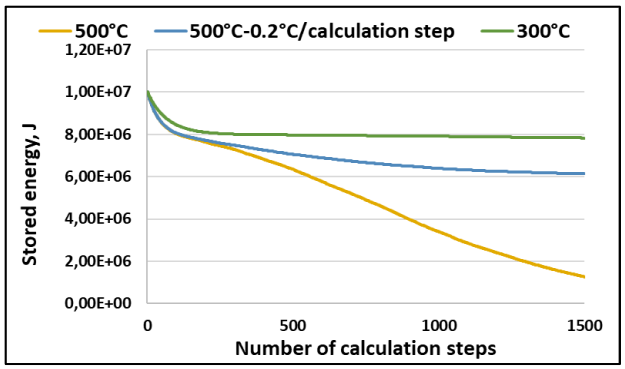

Figure 2. Stored energy changing in function of calculation steps with using different temperature

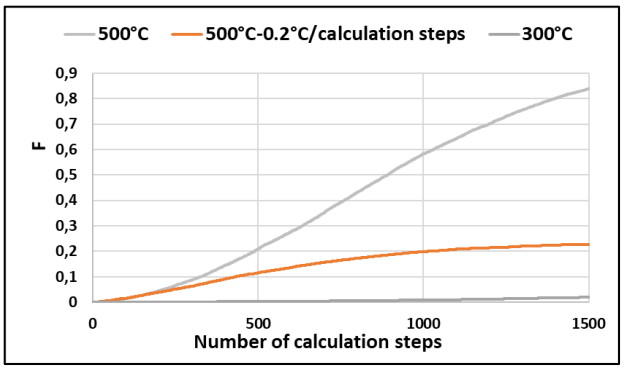

Figure 3. Recrystallized fraction in function of calculation steps with using different temperature

3. Hot rolling simulation by 1D cellular automata

In the real factory practice approximately 400-500 mm thick semi continuous slabs are hot rolled to 5-8 mm final thickness in reverse rolling passes. Number of rolling passes could be different from 15 to 25. Between two hot rolling passes the material lays on roller table and it is cooling. The microstructure is changing during this time not just at hot deformation. Our automata were improved to simulate the material microstructure in case of hot rolling. This capability study focuses on one

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rolling pass and cooling period which is between two rolling passes. We can call cooling period also as holding time. First part of calculation is the rolling and second part of calculation is the cooling. At this stage the stored energy is important factor therefor it was the main point in our experiment with recrystallized fraction. These were analysed with modification of activations energies, recovery limit value and rolling speed.

Figure 4-5. present the recrystallized fracture and stored energy in function of calculation steps where different nucleation activation energy (Qn) were used in calculations. Hot rolling deformation phase were extended to 688 calculation steps and it is followed by 2 sec cooling time which are presented for 2000 calculation step. Increased nucleation activation energy slow down recrystallization. Recrystallization starts at rolling and the smallest activation energy resulted the highest recrystallized fracture. Recrystallized fracture is app. 5% at the highest activation energy and app. 50% at the smallest activation energy at 688 calculation step in rolling zone. It can bee seen also on Figure 5. where curves have local maximum at this point. Maximum value is decreasing with decreasing activation energy that is coming from fast recrystallization and it is getting closer to the starting point of rolling. Recrystallization started sooner at smaller deformation and we got fully recrystallized structure in holding time.

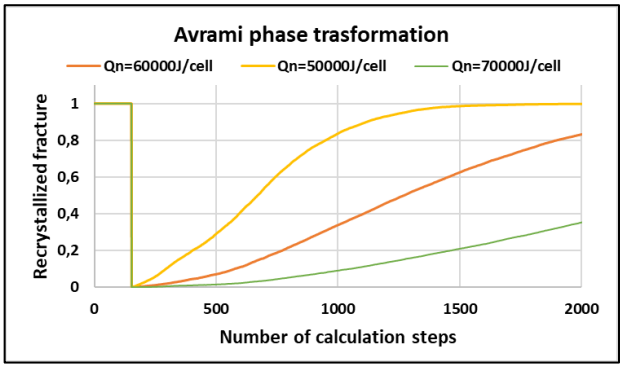

Figure 4. Recrystallized fraction in function of calculation steps with different nucleation activation energy

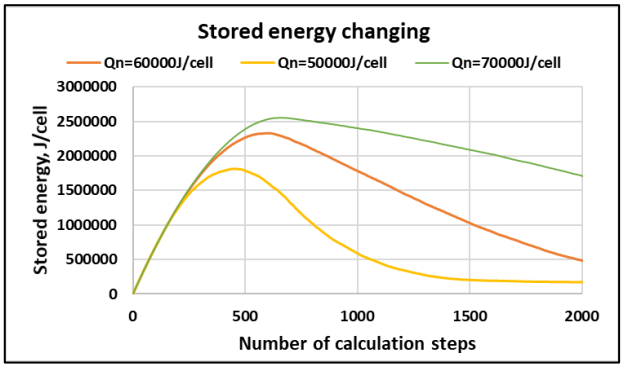

Figure 5. Stored energy in function of calculation steps with different nucleation activation energy

Figure 6-7. present the recrystallized fracture and stored energy in function of calculation steps where different nucleation growing activation energy (Qg) were used in calculations.

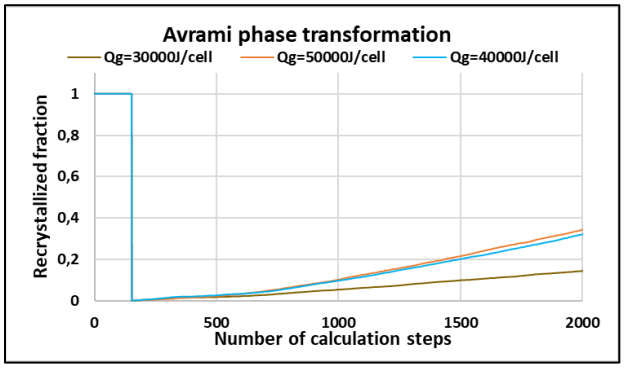

Figure 6. Recrystallized fraction in function of calculation steps with different nucleation growing activation energy

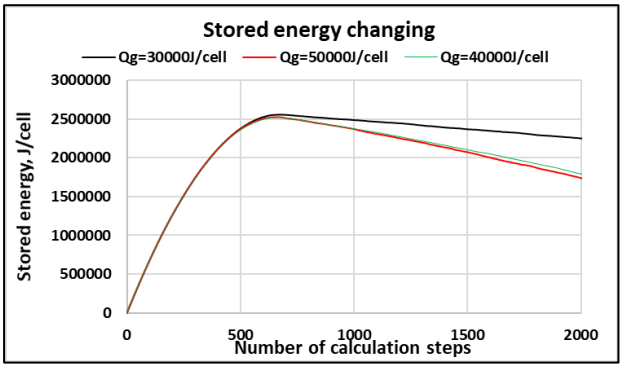

Figure 7. Stored energy in function of calculation steps with different nucleation growing activation energy

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Nucleation growing activation energy were modified during calculations. It has no significant influence in stored energy. When we decrease it the rate of grain boundary movement starts to decrease. There are more deformed volume in the material for nucleus and it gives finer grain structure. The recrystallization can use parallel more stored energy in case of smaller nucleus activation energy.

Effect of Recovery activation energy (Qr) and critical stored energy of recovery (Estr) modification were also examined in this study (Figure 8-9.). There were no significant difference in stored energy results after modification of each values.

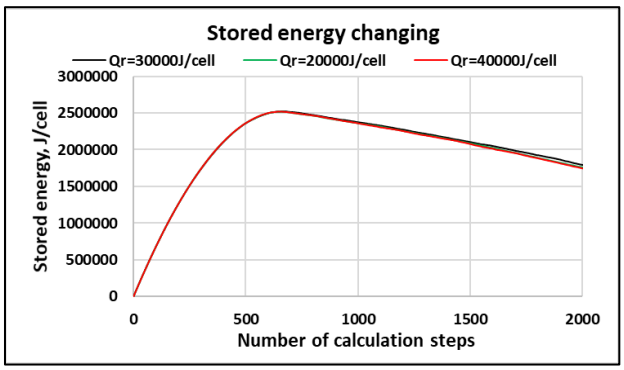

Figure 8. Stored energy in function of calculation steps with different recovery activation energy

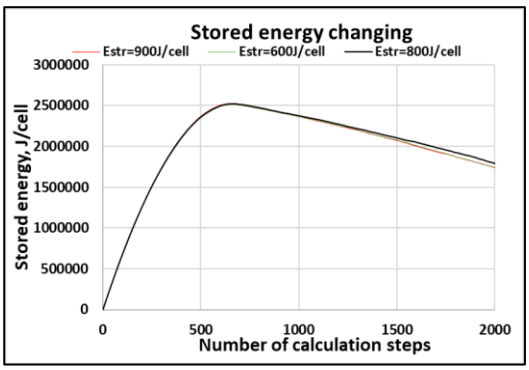

Figure 9. Stored energy in function of calculation steps with different critical stored energy of recovery

Recovery is a really fast process and it uses the stored energy that is the driving force for recrystallization therefor slower recovery has positive effect for faster recrystallization. This aspect of simulation is marked out in curves although it can be seen hardly because curves are close to each other (Figure 8.). The maximum of stored energy curves are at closely the same position and value. Difference can be seen in decreasing value of curves after local maximum point. We got the most intensive decreasing in case of highest activation energy. For the first attitude it seems to be an inconsistency therefore slow recovery helps for recrystallization and in the last stage of rolling and during holding time we have higher stored energy which support faster recrystallization and because of this reason stored energy decreases faster. This automata could respond for these small changings and it gives back expected physical processes.

With modification of critical stored energy of recovery can help us to determine the value of stored energy maximum decreasing in case of recovery. Calculated curves are too close to each other in our study (Figure 9.). Cellular automata calculate by stochastic method. It means that it works with random numbers and it's generation and order affect for the calculation process. Two calculation with same parameters are different so curves change each other position. We can keep this parameter as a constant.

From metal forming point of view the rolling speed is an important parameter. We used different rolling speeds for our capability study which are coming from real industrial practice (Figure 10-11.). Increasing stain generates higher stored energy which is driving force for recrystallization. It is valid also for the increasing rolling speed.

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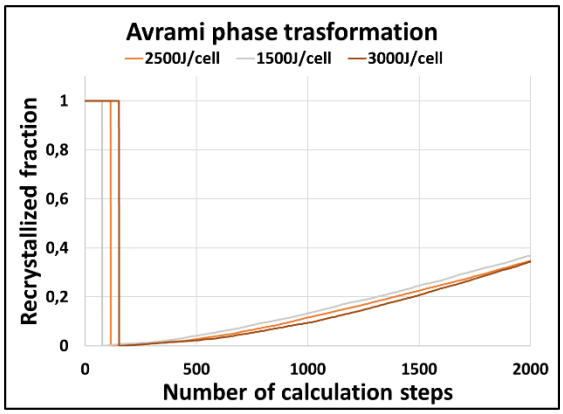

Figure 10. Recrystallized fraction in function of calculation steps with different rolling speed

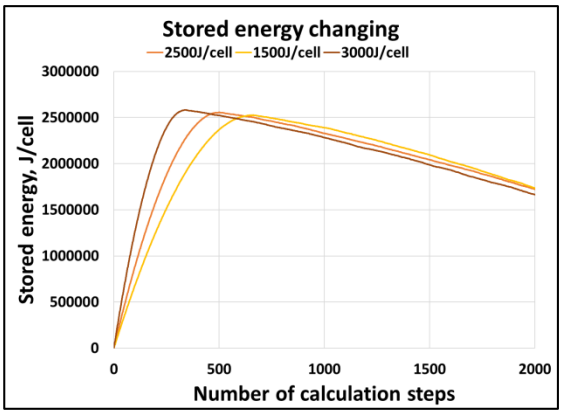

Figure 11. Stored energy in function of calculation steps with different rolling speed

In our experiment the smallest rolling speed gave the smallest stored energy and the recrystallized fraction is reaches the higest value. It has more time for recovery and recrystallization to decrease the stored energy.

Conclusion

Our research is focused on the simulation of hot rolling by 1D cellular automata. Hot rolling is a complex metal forming solution where different physical processes are as work hardening, softening (recovery and recrystallization). Cellular automata is a good method to simulate material properties changing. This can be an opportunity for technology engineer to support their job when they plan a proper technology route. 1D automata works on easiest way. One cell have two neighbours and own state. According the given algorithm every cell calculate and they share information with the neighbour cell and they can change their own state. Our goal was to create the best 1D automata which can handle recovery and recrystallization during one calculation route. In this paper we introduced the results of our capability study. it can bee seen from our results that our automata can differentiate recovery and recrystallization. Stored energy and recrystallized fracture were in focus with the modification of different parameters. According our study we can state that nucleus activation energy has strong effect but nucleus growing and recovery activation energy modification has less effect for stored energy and Avrami phase transformation. The decreasing activation energy accelerate the softening mechanism. Applied rolling speed caused different result in calculation with expected way.

References

[1] Sz. Gyöngyösi, P. Barkóczy, *Sejtautomata Anyagtudományi Alkalmazása*, University of Miskolc, 2012.

[2] R. Espericueta, Cellular Automata Dynamics. Bakersfield College, 1997.

[3] M. E. Doherty, R. D., Hughes, D. A., Humphreys, F. J., Jonas., J. J., Jensen, D. J., Kassner and A. D. Rollett, *Current issues in recrystallization: a review*, Mater. Sci. Eng., 219-274.