Optimizing Grain Structure during Hot Extrusion using the Concepts of Control Theory

J. G. K. Kumar, R. Venkatesh Babu, S. Somasundaram, D.Jayabalakrishnan

[1]Research Scholar, Bharath Institute of Higher Education and Research, Chennai, India

[2]Pro Vice - Chancellor, Bharath Institute of Higher Education and Research, Chennai, India

[3]Department of Mechanical Engineering, Sri Venkateswara Institute of Science and Technology, Thiruvallur, 631203

[4] Department of mechanical Engineering, Chennai Institute of Technology, Chennai, 602109
kumarseries@yahoo.com, rvbaboo76@gmail.com, sahanasoms@gmail.com,
djayabal2001@gmail.com

Abstract

The use of current control theory was done with the goal of achieving optimal microstructure development as a result of hot extrusion. This method uses state space models to portray not just the mechanics of the process, but also the behaviour of its constituent pieces. The issue of selecting process control parameters in terms of strain, strain rate, and temperature in order to obtain prescribed microstructural qualities is tractable. This approach was used to achieve the goal of optimizing the extrusion of plain carbon steel by altering the grain size and several other process variables such as die geometry and ram speed. This investigation's experimental results are quite consistent with the hypotheses produced during the project's planning phase.

Keywords: *Grain Structure, Hot Extrusion, Optimizing, Strain rate, Parameters*

Introduction

The cross section of a billet is reduced during the extrusion process, in which it is pressed through a die. This approach may be used to manufacture completed goods as well as raw materials. The cast structure with a high grain size is polished to the fullest degree during the extrusion processing step. After the initial extrusion process, the material may be sculpted using a variety of ways [1]. Several parameters, including as the billet's initial temperature, area reduction, and the change in strain rate that the material encounters while being deformed, all impact the degree to which the grain is refined during billet extrusion. When moving from billet form to final product shape, "converging dies" are employed, which include gradually changing the cross section of the aperture along the length of the die. This technique is often employed in hot extrusion [2].

The die profile controls how much and how fast the material is stretched as it travels through the die. Conical, cubical, and streamline die shapes with constant actual strain rates are often utilized in hot extrusion. Each of these variables has a significant impact on the final microstructure of the deformed billet. Because of the very high pressures present during hot extrusion techniques, it is usual for materials to undergo dynamic recrystallization [3]. Metals and alloys that respond well to dynamic recrystallization and recovery procedures include copper, nickel, and austenitic steel. These compounds have low stacking fault energies. The flow curves for these compounds never reach more than one maximum value at their highest point under usual circumstances of use [4]. When the plastic strain exceeds a particular value known as Fc, strain-induced grain boundary displacement becomes the primary mechanism for dynamic recrystallization of grains. New nuclei are formed as a result of deformation, and this process is repeated until no grain boundary or incoherent twin boundary sites exist [5].

Nucleation will occur along the boundary between the recrystallized and recrystallized regions of the grains after this first collision, and the process will advance toward the center of the original grains. The microstructure transition during recrystallization is highly dependent on the processing conditions [6]. Because of the intricacy of the processes involved, optimizing and regulating the microstructural development that occurs during the extrusion process is a significant technical difficulty. Extrusion operations need optimal designs and control systems to save money, speed up delivery times, and ensure consistent product quality throughout the process [7]. Existing arbitrary design techniques are incapable of identifying the configuration of tooling systems, deformation rates, die and work piece temperatures, and other critical process parameters. The rising demand for net-shaped components with regulated microstructures and features, as well as the trend toward smaller lot sizes, higher yields, and improved quality, provide a variety of severe challenges to process engineers.

The behaviour of work piece materials, as well as the mechanics of the manufacturing process, need the development of new scientifically based systematic approaches for process design and control [8]. In this paper, we provide a unique method for computing nearly optimal control parameters for hot deformation processes with the goal of achieving microstructural control. This method, which derives from optimal control theory, necessitates the building of state space models of the hot deformation process and the observed material behaviour. This approach for creating control systems consists of two main phases: analysis and optimization [9]. As the first stage, compute the strain, strain rate, and temperature trajectories using a specified set of optimality criteria. These parameters are determined by the kinetics of a certain dynamic microstructural behaviour and the material's inherent hot workability.

These trajectories are applicable to a broad range of hot deformation methods since they are independent of die shape and material flow. In other words, they have no relationship with any of these factors. In the first part of the method, the strain, strain rate, and temperature trajectories are determined. The second stage is to extract process control parameters from these simulations, such as ram velocity profiles and billet temperature. This model might be as simple as a flat sheet or as complex as a finite element model. It might be a variety of things [10]. Using the process simulation model and the principles of optimum control to calculate the process control parameters ensures that the strain, strain rate, and temperature trajectories generated in the first stage are maintained with a high degree of congruence. This investigation will focus on the development and implementation of a novel design technique for microstructure control in hot-extrusion steel.

Materials and Methods

This design technique involves three fundamental aspects to explain and develop the optimization problem: a dynamical system model, physical constraints, and optimality criteria. Models of the material's behaviour and deformation processes are critical in the metal forming process; constraints include the work piece’s heating capacity and the capabilities of the forming equipment. A proper microstructure at the conclusion of the operation, keeping a constant temperature, and/or increasing the rate of deformation is all possible optimization criteria. The current two-stage approach divides the analysis and optimization into two stages: process mechanics and work piece material behaviour.

This enables the technique to address both of these issues more effectively. During the microstructure synthesis process, the ideal microstructure should be used as input, and the goal should be to get the highest possible values for actual strain, strain rate, and temperature. These factors are utilized as inputs during the process optimization phase to determine the best ram velocity, billet temperature, and die shape. The initial phase of development focused on improving workability and fulfilling specified microstructural requirements. The second step's major goal was to obtain localised sections of the deforming work piece that had been exposed to the initial thermo mechanical conditions. It is generally recognized that cutting-edge feedback mechanisms, in conjunction with the creation of appropriate sensors, have the ability to significantly improve the process control solutions generated by this two-step technique.

Material behaviour models that capture the kinetics of critical metallurgical processes such as dynamic recovery, dynamic recrystallization, and grain formation during hot working are necessary for early material system dynamics research and development. A significant amount of research has been conducted on these phenomena in a wide range of metals and alloys. Steel, the subject of the great majority of studies, as well as rare materials like as aluminium, copper, and nickel and their diluted alloys, have all been linked to the characterisation of certain microstructural processes. The vast majority of these studies have focused on steel. The operational deformation processes of specialty alloys such as super alloys, intermetallic, ordered alloys, and metal matrix composites may become well described and modellable within the required temperature and strain rate ranges.

Process modelling has grown in both complexity and widespread acceptance as a tool for process analysis across a wide range of industries. As a result, the number of industries that use process modelling has grown. Because of the precision of contemporary process models, even the most complicated material flow processes, such as non-isothermal three-dimensional deformation techniques, may be investigated. Extensive numerical analysis of the phenomena of the work piece filling the forging die, the corresponding die stresses, and the work piece's post-deformation heat treatment, for example, is increasingly used to validate the designs of the forging and heat treatment processes in the forging industry. This is done to ensure the designs' correctness and efficiency. It is necessary to have both dynamic system models and a declaration of physical limitations in order to develop an optimum control issue. The first stage in the control technique is to define the limiting process parameters for acceptable hot workability based on the significant restrictions imposed on the material's behaviour.

The permitted strain rate and temperature changes for hot working metal alloys are evaluated in this step using material flow stability analysis and an acceptable, practically constant apparent activation energy. These two factors both contribute to the accomplishment of the desired results. A variety of "safe" processing configuration definitions, such as those based on damage nucleation maps, would be consistent with the optimum control formulation. As a result, employ the given optimality criteria to create a certain thermo mechanical trajectory, such as creating specific hot-worked microstructural properties while staying within the allowable processing variation.

Result and Discussion

As previously mentioned, this method is used to regulate the microstructure of the steel being produced during the hot extrusion process. It was possible to calculate the appropriate ram velocity and die profile for extruding steel to create a 40-millimeter grain size using the aforementioned two-stage technique. This has been finished. The basic model for the microstructural development that occurs during metal deformation must explain how the microstructure changes over time as a direct result of the different process factors. An empirical model developed for carbon steel was employed to do this.

The effect of working circumstances such as high heat, stress, and rapid deformation on the microstructure of this steel. The applied deformation strain must be larger than or equal to the critical strain for grain size to be physically significant during dynamic recrystallization. This is because the model utilised in this case allows for a certain kind of recrystallization to occur in the material. The microstructural state of a material is represented by a time-varying vector called the state vector, which is connected to strain and strain rate. This vector is described by the state vector. Grain size is not considered a state variable in this application, but rather a result of the dynamic system. In accordance with previous statements, the strain rate serves as the system's input.

Because of its direct influence on mechanical properties, the microstructure is likely to play a notably important role in deformation processing. A good cost function should therefore put a high value on the ultimate mechanical and microstructural condition of the material. To prevent catastrophic failure and other less severe challenges, the intermediate state of the material must often stay inside certain areas of the state space. In this investigation, the cost function was selected to achieve the requisite ultimate strain of 6 while maintaining the recrystallized grain size at 40 mm throughout the trial. The raw materials average grain size would have been 210 mm if extrusion had not occurred. Optimum die profile for achieving final grain size is shown in figure 1.

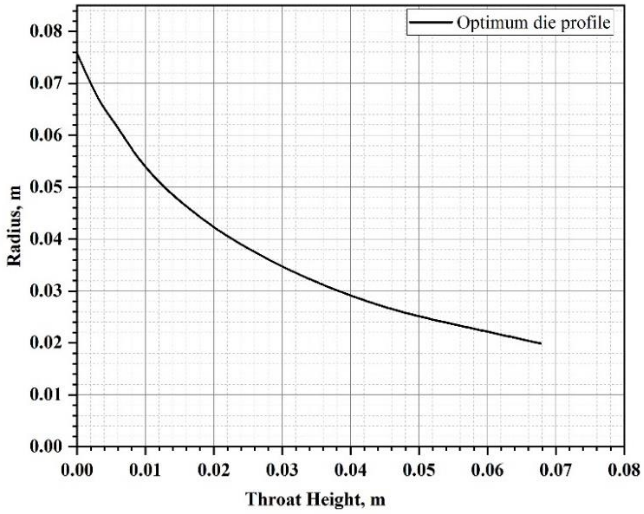

Figure 1. Optimum die profile for achieving final grain size

Optimizing the trajectory proved to be the most successful strategy in this particular case. The optimization procedure provided the needed temperatures and strain rates in addition to the strain. In addition, the expected behaviour of the model for the relevant grain sizes is illustrated. A vertical line that appears at the start of each average grain size trajectory shows recrystallization at the start of the deformation process. Figure 2 shows no recrystallizations because the optimization technique keeps the average grain size constant during the deformation process. This eliminates the possibility of recrystallizations. The optimization approach assures that the average grain size will be as predicted since it maintains the appropriate grain size throughout the recrystallization process. Clearly, the best approach produces both the required end strain and the ideal particle size. Remember that the effectiveness of this strategy is dependent on the amount of information in the microstructural model.

As a consequence, it is critical to prioritise the development of more precise microstructural models for a larger range of material types. It is physically impossible to guarantee that the strain, strain rate, and temperature trajectories measured in the first step are true for every place within the deforming object. This is due to the fact that just a small portion of the object is evaluated in stage one. However, the geometry of the die, ram speed, and billet temperature are all factors that may be changed throughout the deformation process to guarantee that the material is deformed into the correct forms. You may create a second optimization problem to define values for the process variables in order to get the desired trajectories at specific locations inside the material component. When optimising, it is occasionally necessary to do many evaluations of the objective function, which usually needs a high-fidelity finite element simulation of the deformation process.

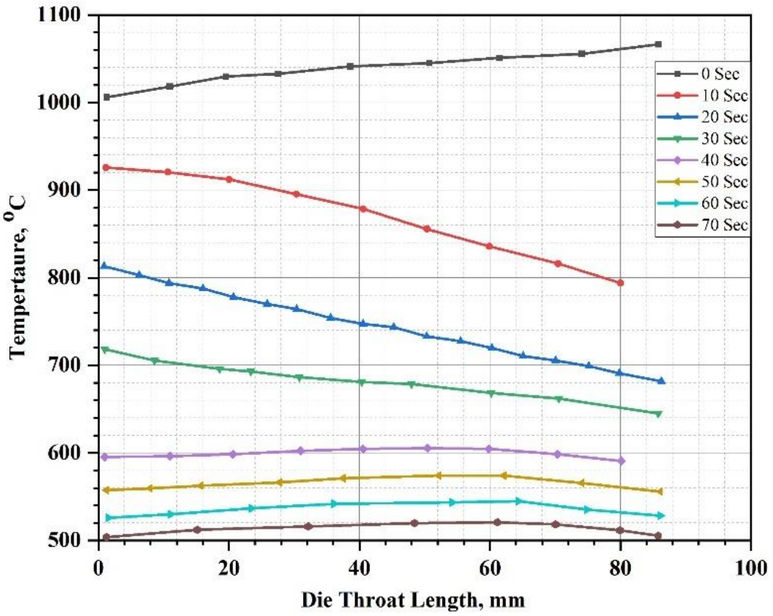

Figure 2. Transient thermal history

Computational modelling with finite elements and hands-on experimentation were used to evaluate the optimization strategies. The extrusion test was carried out using a machine with a force of 7,000 kN. a material's microstructure in its natural state the geometry of the die used in the experiment was chosen to yield the velocity of the ram at a rate of 7.64 mm s-1. The billet measured 275 millimetres in length and 86.18 millimetres in breadth. It was 8.7 to 1 in terms of extrusion ratio. The temperature surrounding the die, follower block, and billet was 764 degrees Celsius, while the billet itself was 1579 degrees Celsius. Only a portion of the billet was extruded since the extrusion process was interrupted by a 90 mm ram stroke. The microstructural development that happened in the deformation zone was the primary focus of this partial extrusion. The billet was put in water to cool after being removed from storage. After the deformation process, the partly extruded billet could not be quenched for sixty seconds. Variation of measured and corrected grain size is shown in figure 3.

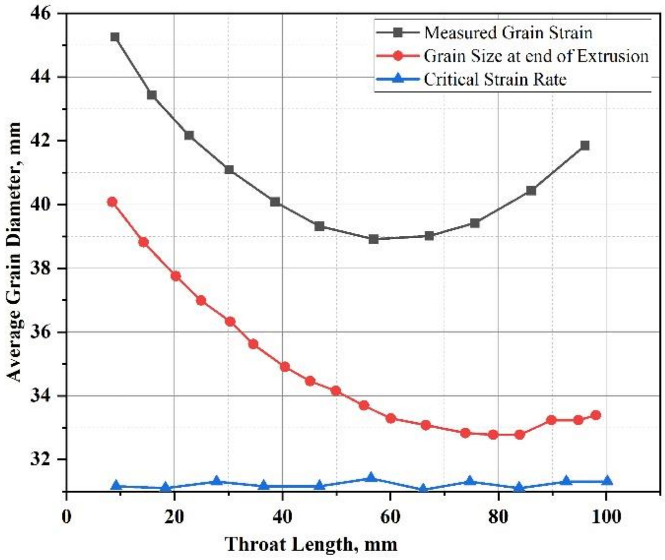

Figure 3. Variation of measured and corrected grain size

This extrusion experiment was replicated in the process simulation software application "Antares." The discretized mesh for billet and die domains is typically six millimetres squared. Each iteration of the ram stroke was prolonged by one complete step in order to do the finite element analysis. Both the temperature response of the die and the nonlinear coupled reaction of the billet were taken into account during modelling. As a result of the deformation heating, the temperature along the centerline of the billet reached 1472 K at the end of the half extrusion.

The total strain was measured to be 3.50 at the centerline of the billet, but 5.57 towards the surface. The change might be attributed to cooling of the billet's surface, which raises the flow stress of the billet's component material. The centerline strain data was used in all of the computations to forecast the microstructure of the billet. This was necessary because changes in friction might further affect the deformation route of a surface area. When partially extruded billets were exposed to air for sixty seconds after entering the die and before being quenched in water at a critical strain, their thermal behaviour was investigated. This was done before to the critical strain. This temperature trend was shown to be related to an increase in grain size as a consequence of grain expansion after deformation as shown in figure 4.

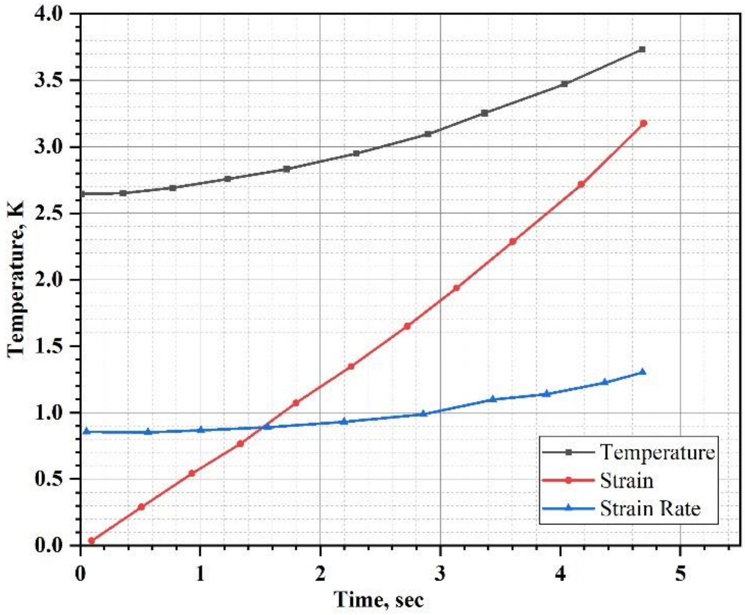

Figure 4. Trajectories of strain, strain rate, temperature, and grain size

The extruded component was trimmed and polished in preparation for the microstructural testing. The grain boundaries were disclosed using a Nital etchant in order to properly measure the material. Researchers discovered equiaxed grains and straight twin boundaries after investigating the distorted portion of the partly extruded specimen's microstructure. The material's unique microstructures can be observed at both the crucial strain point and the die exit of the partly extruded piece. An intercept technique of measuring was employed to offer an accurate estimate of grain sizes.

Histograms were constructed to assess the range of feasible particle sizes as well as the average grain size. The change in grain size along the axis as a function of die throat length was observed at various sites within the deformation zone. Using measurements taken at different positions within the deformation zone of a partly extruded specimen, the average grain diameter is shown as a function of die throat length. The partly extruded component was subjected to water quenching forty seconds after the deformation process was completed. Despite the fact that the austenitic microstructure was predicted to undergo static recrystallization and growth during this time period, a study along the rod's centerline revealed that the microstructure had not altered anywhere along its length. The grain size was measured, and the results showed that the average value was very near to the acceptable value for an extruded rod microstructure [11, 12].

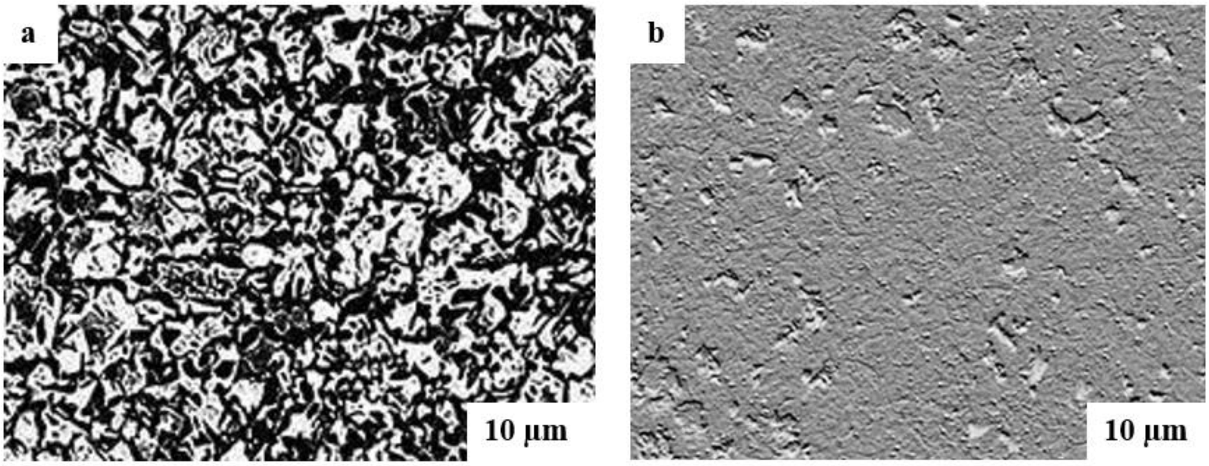

Figure 5. (a) Microstructure of the grain size before Hot extrusion; (b) Microstructure of the grain size before After extrusion

Conclusion

It was proposed that microstructure growth during the hot working process may be regulated using a two-stage approach inspired by optimum control theory. Using this technology enhanced the efficiency of a hot extrusion operation. Initially, using equations for the dynamic recrystallization of plain carbon steel, the ideal deformation route for the product's grain size was found. This was done to get the ideal grain size. The answer was identified by minimising the optimality criteria as much as possible. The strain rate profile during extrusion was constructed in the second phase using geometric mapping in line with the ideal trajectory obtained in the first stage. This step was done to ensure that the best path was adopted. Because the effectiveness of this approach is based on the microstructural model employed during the optimization phase, it is critical that this part of the design process be carried out with the greatest degree of accuracy possible. The geometry of the extrusion die was employed in a verification experiment during the second phase. It was determined whether or not there was a relationship between the change in temperature of the extruded material and the time necessary to complete the quenching process using a process simulation. This temperature development profile was fed into static grain growth equations to calculate the change in quenched grain size that would result in extruded grain size. This adjustment would result in the extruded grain size. A comparison of the actual and intended grain sizes was performed as part of the microstructural evaluation of the extruded specimen. It was determined that the extruded product's grain size approximately matched the optimum pattern generated in the first step.

References

[1] *Seetharaman, R., Seeman, M., Kanagarajan, D., Sivaraj, P. and Saravanan, I., 2020. A statistical evaluation of the corrosion behaviour of friction stir welded AA2024 aluminium alloy. Materials Today: Proceedings, 22, pp.673-680.*

[2] *Jayaseelan, V., Vijayananth, S., Xavier, J.F., Daniel, S.A.A., Kumar, N.M. and Jiang, X.X., 2019. Experimental investigation on bi-axial superplastic forming characteristics of AA6063/SiCp with various percentages of SiCp under various temperatures and pressures. Results in Physics, 15, p.102624..*

[3] *Vijay Ananth, S., Srimurugan, R., Jayaseelan, V., Geethan, A. and Xavier, J.F., 2020, October. Experimental investigation on superplastic forming behavior of AA 6063/SiCp using stir casting. In AIP conference proceedings (Vol. 2283, No. 1, p. 020118). AIP Publishing LLC.*

[4] *Mohrbacher, Hardy. "Property optimization in as-quenched martensitic steel by molybdenum and niobium alloying." Metals 8.4 (2018): 234.*

[5] *Jayaseelan, V. and Kani, K., 2013. Influence of friction factor on extrusion process. In Advanced materials research (Vol. 622, pp. 457-460). Trans Tech Publications Ltd.*

[6] *Peng, Kaixiang, et al. "Contribution rate plot for nonlinear quality-related fault diagnosis with application to the hot strip mill process." Control Engineering Practice 21.4 (2013): 360-369.*

[7] *Jayaseelan, V., Geethan, A., Xavier, J.F., Srimurugan, R. and Vijay Ananth, S., 2020, October. Optimizations of extrusion semidie angle and fabrication of extrusion die. In AIP conference proceedings (Vol. 2283, No. 1, p. 020063). AIP Publishing LLC.*

[8] *Simpson, Timothy W., et al. "Kriging models for global approximation in simulation-based multidisciplinary design optimization." AIAA journal 39.12 (2001): 2233-2241.*

[9] *Azizi-Alizamini, H., Matthias Militzer, and Warren J. Poole. "A novel technique for developing bimodal grain size distributions in low carbon steels." Scripta Materialia 57.12 (2007): 1065-1068.*

[10] *Veerasundaram, J., Kani, K., Murugesan, S. and Nallamuthu, R., 2022. Effect of extrusion ratio and die angle on the microstructure of an AA6063/SiC composite. Materials Testing, 64(6), pp.874-883.*

[11] *Veerasundaram, J., Kani, K., Nallumuthu, R. and Thangaraj, M., 2022. Experimental and theoretical investigation of extrusion load for AA6063/SiC extruded composite billet. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, p.09544089221111283.*

[12] *Sivaraj, P., Seeman, M., Kanagarajan, D. and Seetharaman, R., 2020. Influence of welding parameter on mechanical properties and microstructural features of resistance spot welded dual phase steel sheets joint. Materials Today: Proceedings, 22, pp.558-562.*