

# The effect of alloying elements for the hot workability of AlMn1 aluminium alloy

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**Abstract.** There is a wide range of applications of aluminium alloys that contain manganese alloying element. This is mainly due to its good durability, corrosion resistance and cost effectiveness. The biggest proportion of manganese alloying element is in solid solution during the casting process and solidification. Moreover the remaining manganese content can be found also in the casted aluminium in precipitation form. Because of high production volume it is essential to optimise the production process in every respect to assure more economical production. Our experiment focused on one of the most important production steps of rolled products that is hot rolling. During hot forming the plastic deformation and the softening processes takes place in parallel in a complex system. In our experiment we carried out physical simulation with Gleeble thermomechanical simulator. Three aluminium-manganese alloys were compared with different chemical compositions. We applied hot compression tests and then we studied the measurement results.

## 1. Introduction

There is wide range of applications of aluminium alloys that contain manganese alloying element because it has good formability and corrosion resistance. These are sold and used in high volume around the world in rolled forms like strip, sheet and shate. They have many industrial applications for example cooking and automotive industry where these alloy is used for heat changer products.

One method to produce rolled products is to use semi-continuous cast ingots for it [1, 3]. These ingots are fabricated after casting to guarantee a suitable geometry, and a clean surface composition. To reach the required thickness the ingot is rolled. The reduction of thickness in an economic way can be fulfilled by hot rolling where the work hardening [2, 5] and the annealing of the aluminium [4, 6] occur in the same time or closely. High thickness reductions can be reached by applying smaller forming forces during hot rolling with less energy consumption. For hot rolling it is necessary to heat up the material to hot rolling temperature. It is essential to apply such a temperature during preheating cycle where the homogenization of the ingot can be achieved. At solidification micro-segregations exist in the material that causes concentration differences. At the appropriate homogenization temperature these concentration differences start to equalize and this heat treatment refer to sure hot deformation at hot rolling [5, 6].

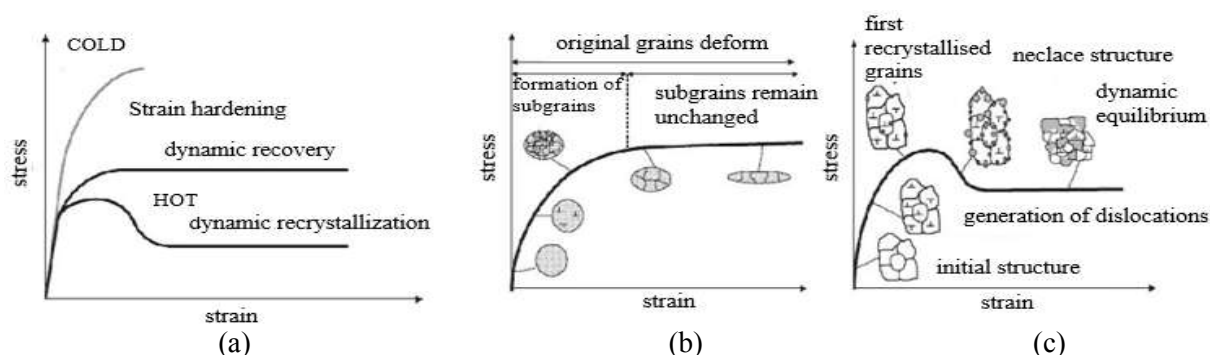
Work hardening effect starts during metal forming. Dislocation movements support the plastic deformation in metals. Dislocation is a one dimension lattice defect. During plastic deformation the number of dislocations are multiplied. When the number of them such a volume that they hinder of each



other in their movement the material getting harder and for further forming of material it is essential to apply higher forming force that generates higher stress in the material.

When the temperature is sufficient, in relation to amount of strain the annealing starts in the material. These two phenomena change the dislocation structure and we talk about recovery and recrystallization. Dislocations are organized at recovery. Aluminium tends to recovery such that dislocations are easily moved from their position. These organisations of dislocations can be small as they compose lines and set up low angle grain boundaries and in the original grains a new sub-grain structure develops. Because of the organization of dislocation structure these dislocations do not hinder each other with high effort, hence the necessary stress is decreasing for the deformation. If we measure stress during deformation in terms of the applied strain in that situation the recovery compensates the work hardening effect when the recovery is achieved then ready state stress develops.

The other process that causes annealing is the recrystallization. In the deformed material volume fraction small nucleuses are developed then they are growing. If we study the stress for deformation as a function of the strain, in that case the curve has a local maximum. This is the location where the recrystallised grains are growing continuously and in parallel the deformed volume fraction is decreasing and the stress achieves steady state values. Nucleuses develop mostly on the grain borders so therefore the result at the local maximum of the curve a typical necklace structured grains development where the recrystallized new grains are located on the formed grain borders. When these above mentioned phenomena occur during hot forming we are talking about dynamic recovery (Fig. 1.b) and dynamic recrystallization (Fig. 1.c).



**Figure 1.** The relationship of strain and stress: (a) comparison of cold and hot forming, (b) dynamic recovery and (c) dynamic recrystallization [7]

Aluminium-manganese alloys belongs to workable and non-precipitation hardening alloys. During preheating of the material up to hot rolling temperature the manganese starts to precipitate from the solid solution. The kinetics of precipitation process has influence for the size of new phases and also for those processes that happen during hot rolling. Manganese element has a special feature as it has low solid solubility in the aluminium. During the solidification the manganese precipitates with the iron atoms in the form  $Al_6(Mn,Fe)$  that is an eutectic intermetallic phase. The volume, size and the distribution of intermetallic phases and the manganese volume in solid solution are changing during solidification as a function of the cooling rate. The ratio of Fe-Mn in the intermetallic phase changes during homogenization and also the manganese in solid solution starts to precipitate mostly in  $Al_6Mn$  form. The developed microstructure, concentration of alloying elements, the size and distribution of precipitations and grain structure after homogenization is the initial state at the beginning of hot rolling.

During hot rolling the work hardening and the start of the regeneration process of crystals determine the properties of the microstructure that is very important to take into consideration during the technology preparing. In case of aluminium alloys at dynamic annealing the dynamic recovery and the dynamic recrystallization are realised in the same order of magnitude rate.

These two phenomena determine together the hot rolled grain structure. Further processes like cold rolling and heat treatment change the hot rolled microstructure but even so the hot rolled microstructure

still influences the final property of the end-product. The hot compression test of these alloys is the method to study this complex system with different parameters. The main important parameters are the forming temperature, strain and strain rate.

## 2. Material and methods

In our experiment three types of AlMn1 aluminium alloy were compared. The chemical composition of them were different as shown in Table 1. EN AW 3003 aluminium alloy was our base material and we compared the other ones against it.

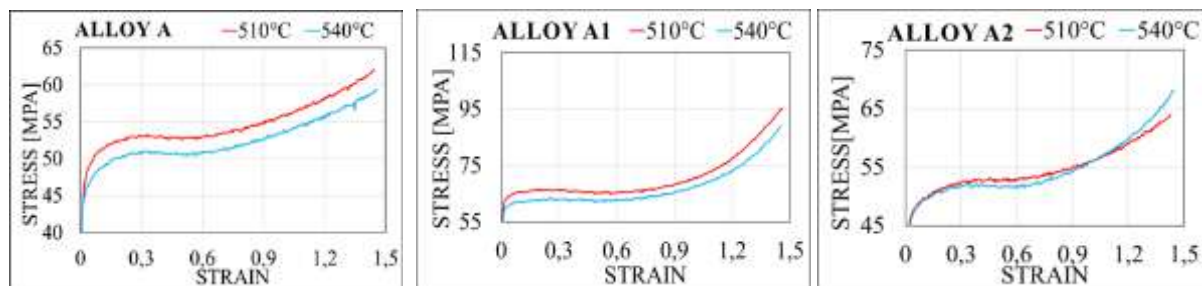
**Table 1.** Chemical composition of the measured material (m%)

	Alloy code	Si%	Fe%	Cu%	Mn%	Mg%	Ti%
<b>EN AW 3003 (base)</b>	A	0-0,6	0-0,7	0,05-0,2	1-1,5	-	-
<b>Difference from EN AW 3003</b>	A1	+0,5	-	+0,5	+0,1	+0,2	+0,1
<b>Difference from EN AW 3003</b>	A2	-0,2	-0,3	+0,5	-	-	+0,1

Physical simulation was carried out in this experiment. Uniaxial hot compression measurements were taken by Gleeble thermomechanical simulator. We studied the microstructure changes during hot deformation by taking into consideration the effect of main alloying elements which are manganese, copper, magnesium and silicon. For this experiment samples were taken from cast aluminium and were subjected to homogenization heat treatment in laboratory furnace. We applied two different homogenization characteristics for comparison. Samples were in the furnace at 510 [°C] for 1 hour and the other was at 540 [°C] for 6 hours holding time, then at the end of the cycle they were cooled down in cold water to room temperature. From the homogenized material smaller 16x27 mm cylindrical test specimens were prepared for the hot compression test that were formed at 380 [°C] and at 500 [°C] by using 0,2 and 20 [1/s] strain rates. Specimens were heated up at a 2 [°C/sec] rate to the hot forming temperature and were held at this temperature for 90 seconds before the forming. Every specimen was compressed by 1,5 strain and at the end these were quenched in cold water to cool down to room temperature in order to freezing the microstructure. The temperature was controlled during the tests and the strain and the stress values were registered. Specimens were prepared for metallographic examinations. Microsection were taken perpendicular to the forming direction then polished and etched. Struers LECTRO-POL 5 type of electropolishing device was used for etching with applying special Barker type of liquid. Pictures were taken by Zeiss AxioVert40 type of optical microscope in polarized light with Zeiss ICC camera.

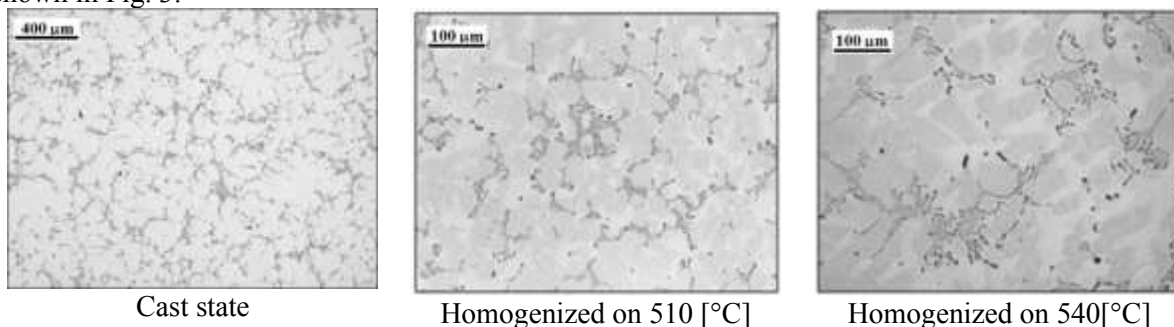
## 3. Results and discussion

Based on the experiment results we studied the effect of each of the applied measurement parameters for the hot workability and for the developing new microstructures by taking into consideration the specimens preheating circumstances known as homogenization heat treatment. During the experiment the registered compressing stress was plotted in accordance with the strain. At the first step we analysed the effect of the two different homogenization treatment processes for the hot workability. The strength of homogenized specimens at 540 [°C] was decreased for every alloy and at every hot compression test with compared with the homogenized specimens at 510 [°C]. It is shown in Fig. 2.



**Figure 2.** Comparison of homogenization 510 [°C] and 540 [°C]:  
The stress curves of tested alloys with 380 [°C] and 0,2 [1/s] strain rate.

The reason for this is that the higher temperature and its holding time during homogenization treatment has influence for the microstructure of the cast specimen. It is changed. The manganese volume that is in solid solution in the aluminium matrix starts to precipitate in the measured alloys as shown in Fig. 3.



**Figure 3.** Optical microscopic microstructure of A1 alloy.

The higher temperature and its holding time supports the diffusion of atomic manganese element. By reason of the higher energy state the size and the structure of precipitation is different now along with the intermetallic phases which are developed during solidification. These together cause the changing of the strength of material. The volume of manganese in solid solution starts to decrease with increasing the temperature so thus the solid-solution hardening effect of manganese are getting decreased when precipitations are appeared. These phenomena cause the decreasing stress as shown in Fig. 2.

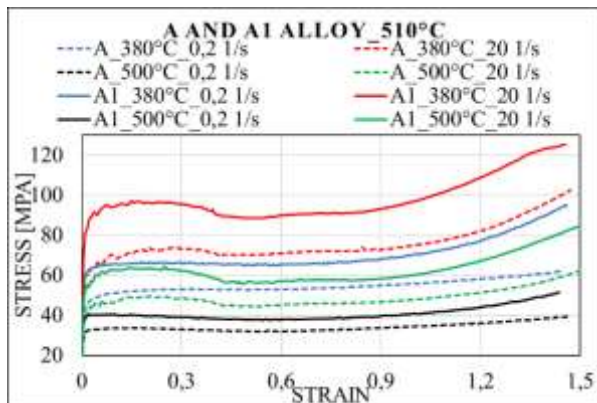
In further diagrams in this article the stress curves will be shown two forming temperatures and strain rates applied to the base alloy “A” is marked by dashed curves for easiest segregation (Fig. 4-7.)

As a first step the strain rate effect was studied. On the evidence of the curves it can be determined for the same alloy and hot compression temperature and with the smallest strain rate the stress of the measurement is the lowest. But conversely the higher strain rate causes higher stress in the formed material. By increasing the strain rate the tool of the equipment facing with higher resistance. If we are increasing the temperature then the stress is continuously decreasing for the same alloy with the same strain rate hence the same deformation can be reached by lower forming force. It is seen that the highest temperature and small strain rate gives the lowest stress results, whereas the lowest forming temperature and highest strain rate cause the highest stress in the material that resulting in two or three times higher strength. This phenomena is representative for the whole experiment.

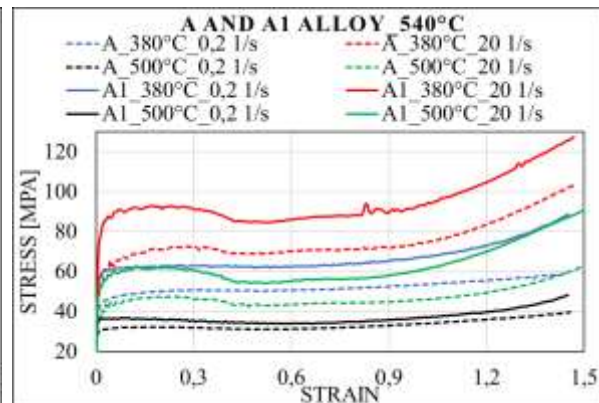
From the workability point of view it is possible to make obvious distinction between alloys. Increasing alloying elements generated higher stress in our experiment. The basic “A” alloy can be formed easiest if it is followed by “A2” and finally “A1” alloy. The last one has the highest Si, Mn, Mg and Ti alloying element. From the stress curves the difference can be seen between alloys. The continuous curves of “A2” and “A1” specimens are above of the base “A” alloy with dash curves almost in every case. There were only two exemptions are which will be discussed later (Fig. 6. and 7. black curves).



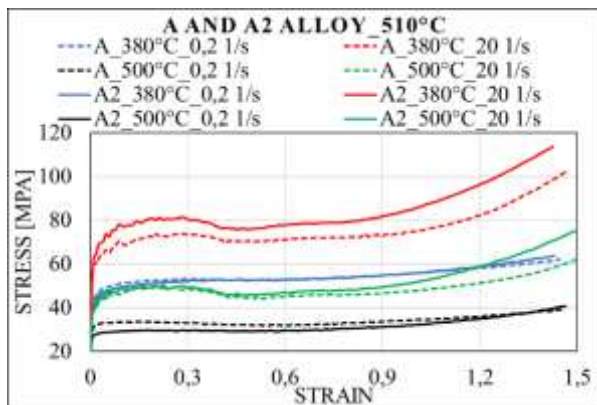
Independently from the alloys with 380 [°C] and 20 [1/s] parameters the “A1” and “A2” alloy curves divide wider from “A” alloy dashes curves. These hot compression parameters caused the biggest difference in stress result comparing these alloys. With increasing forming temperature up to 500 [°C] and with decreasing the strain rate the strength of “A1” and “A2” alloys approach the results of the base “A” specimen. The curves of stress values are close to each other and the order of magnitude is similar at the same location.



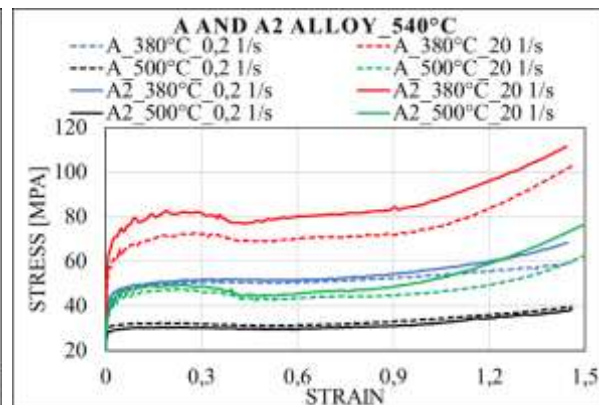
**Figure 4.** Comparison of alloy A and A1\_homogenisation: 510 [°C]



**Figure 5.** Comparison of alloy A and A1\_homogenisation: 540 [°C]

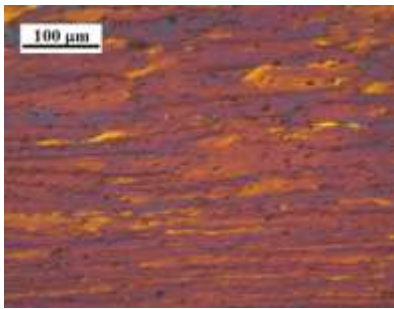


**Figure 6.** Comparison of alloy A and A2\_homogenisation: 510 [°C]

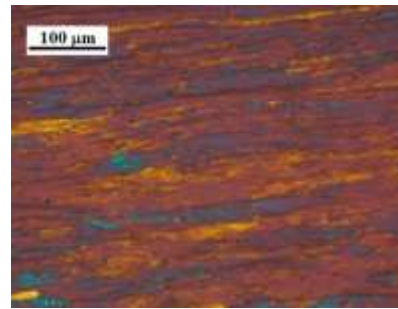


**Figure 7.** Comparison of alloy A and A2\_homogenisation: 540 [°C]

Alloying elements also hinder the movement of dislocations so where dissimilar atoms are located in the basic aluminium matrix these area of the material are intensely getting harder during plastic deformation. At these areas where the dislocation density and the lattice distortion is high during hot rolling the dynamic recovery starts sooner and moreover it is getting softer. The curves at 500 [°C] and 0,2 [1/s] parameters on Fig. 6 and 7. don't have the same trend like the others. The curves of “A2” alloy is working with lower stress values. It is assumed that the dynamic recrystallization started with these forming parameters because the deformation occurs with lower forming when compared with specimen “A2”. The difference here is low. On the optical microscopic picture of the specimen it can be seen inconspicuously as new nucleus and recrystallized small grains are developed under hot forming Fig. 8 and 9.

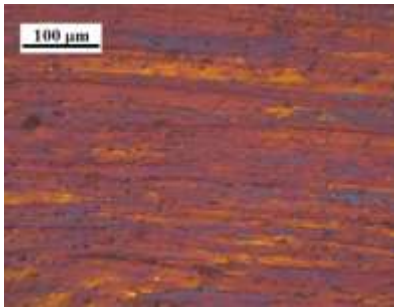


**Figure 8.** Alloy “A2” homogenization at 510 [°C] hot forming at 500 [°C] with 0,2 [1/s] strain rate

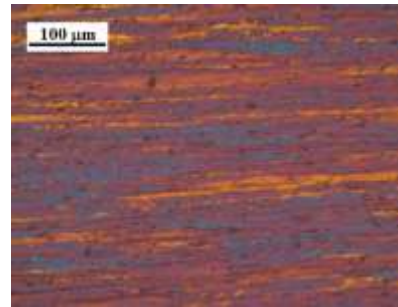


**Figure 9.** Alloy “A2” homogenization at 540 [°C] hot forming at 500 [°C] with 0,2 [1/s] strain rate

For the same temperature but with higher strain rate the registered stress values were with about 20 [MPa] higher. The microstructure of these specimens show that the grain structure is more formed and a shape that represents a typically cold formed structure (Fig. 10 and 11).



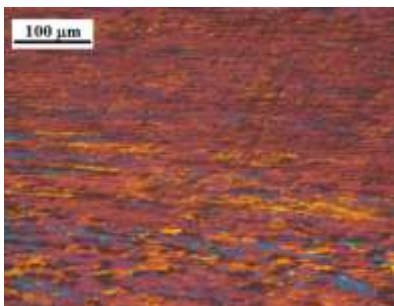
**Figure 10.** Alloy “A2” homogenization at 510 [°C] hot forming at 500 [°C] with 20 [1/s] strain rate



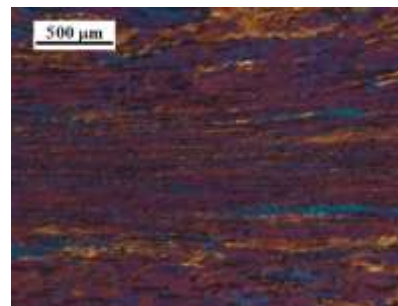
**Figure 11.** Alloy “A2” homogenization at 540 [°C] hot forming at 500 [°C] with 20 [1/s] strain rate

Curves become flattened with increasing strain. The measured stress didn't grow intensively. With these applied parameters dynamic recovery occurs rather in the material than the recrystallization. Dynamic recovery can't be seen on the microstructure on these pictures with this magnification.

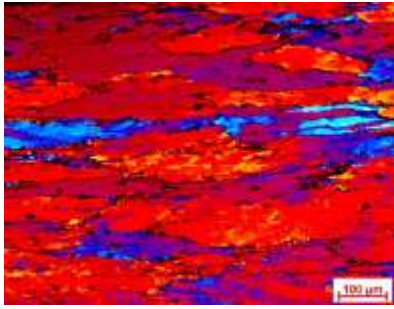
We took into consideration the microstructure and noted that the nucleation and dynamic recrystallization started only from 500 [°C] with 0,2 [1/s] parameters in case of every measured alloy (Fig. 8; 9; 12; 13; 14 and 15). Besides the formed grains the new modified grain structure can be also seen.



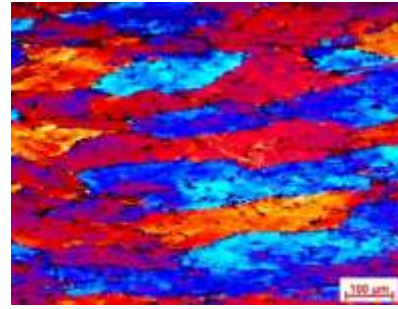
**Figure 12.** Alloy “A1” homogenization at 510 [°C] hot forming at 500 [°C] with 0,2 [1/s] strain rate



**Figure 13.** Alloy “A1” homogenization at 540 [°C] hot forming at 500 [°C] with 0,2 [1/s] strain rate

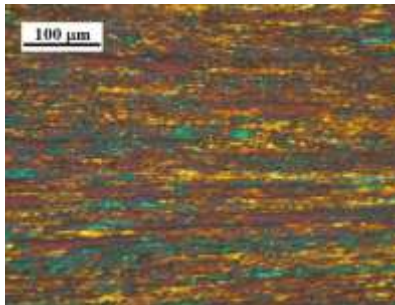


**Figure 14.** Alloy “A” homogenization at 510 [°C] hot forming at 500 [°C] with 0,2 [1/s] strain rate

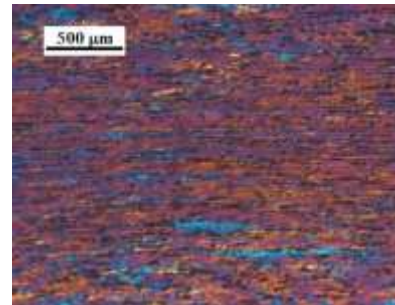


**Figure 15.** Alloy “A” homogenization at 540 [°C] hot forming at 500 [°C] with 0,2 [1/s] strain rate

The microstructure refers to cold deformation in the case of other hot forming parameters (Fig. 10; 11; 16 and 17).



**Figure 16.** Alloy “A” homogenization at 510 [°C] hot forming at 380 [°C] with 0,2 [1/s] strain rate



**Figure 17.** Alloy “A1” homogenization at 510 [°C] hot forming at 380 [°C] with 0,2 [1/s] strain rate

If we compare the trend of the evaluated curves with the theoretical curves on Fig. 1.b it can be determined as in our experiment that instead of dynamical recrystallization dynamic recovery is established. The dynamic recovery under hot compression compensates the hardening effect in the specimen when it starts. This can be seen in the curves when at about 0,1 strain the stress values jump up suddenly where the dynamic recovery starts up and the stress is closely steady-state. On Fig. 1.c the stress results have a significantly strong decreasing in the curve that represent the dynamic recrystallization. This is the state when dynamic recrystallized grains develop in the formed material and with these phenomena the material is getting softer. In some case our curves are similar but these are coming from the unsteadiness of measurement. Our curves have a local maximum but the stress decreasing is not so significant as show in Fig. 1.c. Spectacularly it happened only in our experiment at 20 [1/s] strain rate. We suppose that it is coming from the applied high strain rate which has higher effect with the amount of friction between the sample and the working tool of the device. In our case there is no dynamic recrystallization that can be seen in the microstructure in Fig. 10 and 11. Because of friction the trend of our curves in some cases jumps up from strain 0,9-1,2 values. At this stage at higher reduction of the specimen it is getting wider because of the material flow and there is bigger surface area of the specimens in contact with the tool.

#### 4. Summary

There is wide range of applications of aluminium alloys that contain manganese alloying element, thanks to its good workability and corrosion resistance. One possibility is to produce rolled products using semi-continuous cast ingots for it. The manganese has a feature of small solid solubility in the aluminium thus during solidification the intermetallic phase in the aluminium is configured with the iron. Some volume of manganese stays in solid solution. It is essential to heat up the cast ingot for hot rolling. In accordance with the pre-heat treatment before hot rolling the remaining manganese starts to precipitate from solid solution that has later high effect for the further material property. In our experiment we studied the effect of preheating (homogenizing heat treatment) and we carried out hot compression experiments to simulate the hot rolling in laboratory conditions. Different forming temperatures and strain rates were applied. Based on the recorded data and with experimental results three aluminium alloy were compared. During hot forming of aluminium-manganese alloys the dynamic recovery is the typical phenomena and in our experiment it was dominant. The nucleation of new grains and the recrystallization started only from 500 [°C] temperature with 0,2 [1/s] strain rate in case of every alloy. The stress result was smaller during hot compression test in case the of higher temperature homogenization. With increasing alloying elements of the specimens harder material is generated, however the homogenizing heat treatment has a stronger effect for the strength. Some alloying elements assist with the precipitation of AlMn intermetallic phases and in this case the difference can be higher.

#### Acknowledgement

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