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# Structure and strain state of aluminum bars at the initial phase of extrusion

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**Abstract:** The structure of insufficiently deformed areas at the non-steady phase of extrusion was studied. The tests at Kamensk Uralsky Metallurgical Works using a 120 MN press and 800 mm dia. container, in order to extrude a 355.6 mm dia. Bar was performed. The bar material is the Al–Mg–Si AD33 aluminum alloy (GOST 4784), similar to ASTM 6061. The percentage reduction was 80 %, and the reduction ratio was 5.06. After that, the macrostructure, microstructure, and average grain size along the radius, mechanical properties at room and elevated temperatures were investigated. It was found that the extruded bar macrostructure is fine-grained, homogeneous, and dense, with no nonmetallic or intermetallic inclusions. The cross-section contained several structures. The central part is weakly deformed preserving the dendritic cell structure inherited from the casting. At the circumference, a streaked structure is formed. Its components are crushed and uniformly distributed. We measured the strength at elevated temperatures and compared the results to the data available in the literature. The tested material strength almost doubled, thus indicating its incomplete softening. The ductility was also performed. The DEFORM-2D software, in order to simulate the low reduction of extrusion was used. The metal at the circumference is exposed to a greater strain from the extrusion beginning. A step-by-step analysis indicated that at the first step, the strain is localized near the die hole. In the second step, a rigid area is formed in the vicinity of the die/container liner interface. The circumference layer of metal with a 1.75–2.00 reduction of area is formed. At the bar center, this range is 0.75–1.00 (half of the circumference value). In the third step, the circumference layer with an elevated strain has a wedge-like shape. In the fourth step, the circumference layer (with elevated strain) has an equal thickness along the extrusion axis. This indicates the steady phase. The plastic strain at the bar front end is higher at the circumference than in the center. This confirms the structural analysis results. They show that the central part of the bar may retain its cast structure, while the circumference is deformed. If the bar central part is required to have some specific properties, the bar has to undergo another manufacturing operation to increase the accumulated strain. Re-extrusion processes the areas insufficiently deformed during the first extrusion.

**Keywords:** extrusion, plastic strain, metal structure, heterogenic properties, finite element modeling, simulation

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# Структурное состояние и деформации заготовки из алюминиевого сплава в начальной стадии прессования

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**Аннотация:** Выявлены особенности строения зон недостаточной проработки металла в нестационарной стадии прессования. В условиях ОАО «Каменск-Уральский металлургический завод» (Россия) на прессе номинальным усилием 120 МН выполнено прессование слитка из контейнера диаметром 800 мм с получением прутка диаметром 355,6 мм. Материал слитка – алюминиевый сплав АД33 (ГОСТ 4784) – аналог сплава 6061 по стандарту ASTM системы Al–Mg–Si. Относительное обжатие в таком процессе составляло 80 %, а коэффициент вытяжки – 5,06. Дальнейшее исследование включало изучение макроструктуры, микроструктуры вдоль радиальной координаты, определение среднего размера зерна вдоль радиальной координаты, испытания механических свойств при комнатной и повышенной температурах. Установлено, что макроструктура выходной части прутка – мелкозернистая, однородная, плотная, неметаллические и интерметаллидные включения отсутствуют. Однако по поперечному сечению выявлена разноструктурность: в центре структура демонстрирует слабодеформированное состояние, сохраняя рисунок строения дендритных ячеек, унаследованных от литья; на периферии структура имеет строчечное строение, ее составляющие малого размера и равномерно распределены. Получены значения прочностных свойств при повышенных температурах и выполнено сравнение с известными из литературы данными. Материал в опытах оказался прочнее почти в 2 раза, что говорит о его неполном разупрочнении. Также выполнено сравнение пластических свойств. В расчетной части с помощью программного модуля DEFORM-2D проведено численное моделирование прессования с малым коэффициентом вытяжки. Выявлено, что металл на периферии подвергается большей степени деформации с самого начала процесса. Отслеживание ситуации по шагам показало, что на первом шаге деформации локализованы вблизи отверстия матрицы, на втором – наблюдалось образование жесткой зоны в окрестности стыка матрицы и рабочей втулки контейнера. В периферийной области установился слой металла со степенью деформации 1,75–2,00. В то же время в центре этот диапазон снизился до 0,75–1,00, т.е. значения оказались практически в 2 раза меньше. На третьем шаге периферийный слой с повышенным уровнем деформации имеет клинообразную форму, на четвертом – периферийный (с повышенной степенью деформации) слой имеет равную толщину вдоль оси прессования, что говорит о наступлении стационарной стадии. Для переднего конца прутка на периферии показатель пластической деформации выше, чем для центральной части. Это подтверждает результаты структурного анализа, где было показано, что в центральной части может сохраняться литая структура, в то время как на периферии возникают все признаки наличия деформированного состояния. Таким образом, если возникает необходимость использования этой части заготовки в качестве материала с необходимым уровнем свойств, то придется применить технологическую операцию с увеличением накопленной степени деформации. При запланированной повторной обработке прессованием создаются условия для проработки областей металла, недостаточно деформированных при первичной обработке.

**Ключевые слова:** прессование, пластическая деформация, структура металла, неоднородность свойств, метод конечных элементов, численное моделирование

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## Introduction and problem statement

Extrusion is a common manufacturing process used for making aluminum or other light metal parts [1]. The process should be quickly adjusted to make new parts since the product range can be extremely extensive. This means replacing just one tooling for extrusion — the die. Moreover, extrusion improves metal ductility by irregularly compressing the metal from all sides. Indeed, the ductility of aluminum alloys is often low [2]. The extrusion process is required in order to increase ductility [3, 4].

On the other hand, extrusion results in a irregularly strain distribution [5], especially in the initial phase. This phase is commonly referred to as unsteady. It begins with closing the opening between the bar and tooling, and the metal expanding and filling the extrusion container [6, 7]. Next, the bar front endis pushed through the opening in the die. At this phase, the strain gradually penetrates the metal. However, the compressive stress is not yet high enough which may lead to cracking [8].

Finally, the process reaches the steady phase. This is when the strain field is stabilized. There is a chance to obtain consistent metal properties and structure the entire bar length [9], although some inconsistencies across the cross-section will most likely remain [10—12]. In this case, the bar outer shell experiences extensive strain, which may lead to cracking [13].

A question arises: how long is the unsteady phase? We need to know this, in order to determine which bar part meets the specifications.

Few studies address this question. It should be noted some papers about this topic [14, 15]. Finite element modeling can be used to simulate the stresses and strains in real extrusion processes [16, 17].

The study purpose is to identify the structure of insufficiently deformed areas at the unsteady extrusion phase.

## Industrial test conditions

The tests was performed at Kamensk Uralsky Metallurgical Works using a 120 MN press and 800 mm dia. press container, in order to extrude a 355.6 mm dia. bar. The bar material is the Al—Mg—Si AD33 aluminum alloy (GOST 4784), similar to ASTM 6061. Its required chemical composition is (wt.%): 0.8—1.20 Mg; 0.4—0.8 Si; 0.04—0.35 Cr; 0.15—0.40 Cu. The actual metal composition was as follows (wt.%): 1.0 Mg; 0.6 Si; 0.14 Cr; 0.19 Cu; 0.58 Fe; 0.10 Mn; 0.02 Zn; 0.06 Ti. Some of the elements are acceptable impurities.

The percent reduction was 80 %, and the reduction ratio was 5.06. After the test, we studied:

— macrostructure;
— microstructure along the radius;
— average grain size along the radius;
— mechanical properties at room and elevated temperatures.

For the tests, the samples was cut off from the front end of the bar. Fig. 1 shows the metal macrostructure (1/4 cross-section). The bar front end macrostructure is fine-grained, homogeneous, and dense, with no non-metallic or inter-metallic inclusions.

The bar front end macrostructure is dense, with no non-metallic or inter-metallic inclusions in the cross-section. We identified several structures in the cross-section:

— the center (Fig. 2, *a*) is weakly deformed, preserving the dendritic cell structure inherited from the casting;

— the same structure is at half of the radius (Fig. 2, *b*) from the center;

— at the circumference (Fig. 2, *c*), a streaked structure is formed. Its components are crushed and uniformly distributed.

The streak structure indicates that the main elongation occurs along the extrusion axis. In the cylindrical coordinate system, the other principal strains (tangent and radial) are compression strains.

The average grain size at the bar center at half of the radius from the center was 190 μm, and 30 μm at the

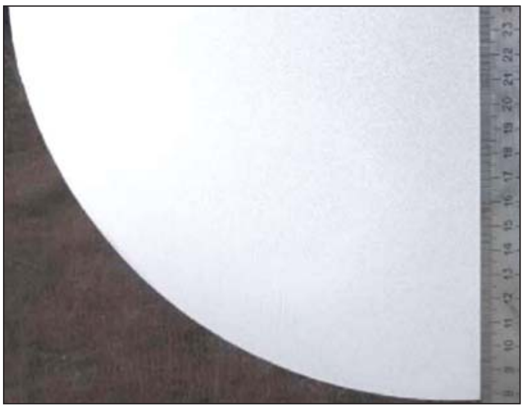

**Fig. 1.** The bar front end macrostructure, 355.6 mm dia. (1/4 cross-section)

**Рис. 1.** Макроструктура выходной части прутка диаметром 355,6 мм (поперечное сечение, четверть темплета)

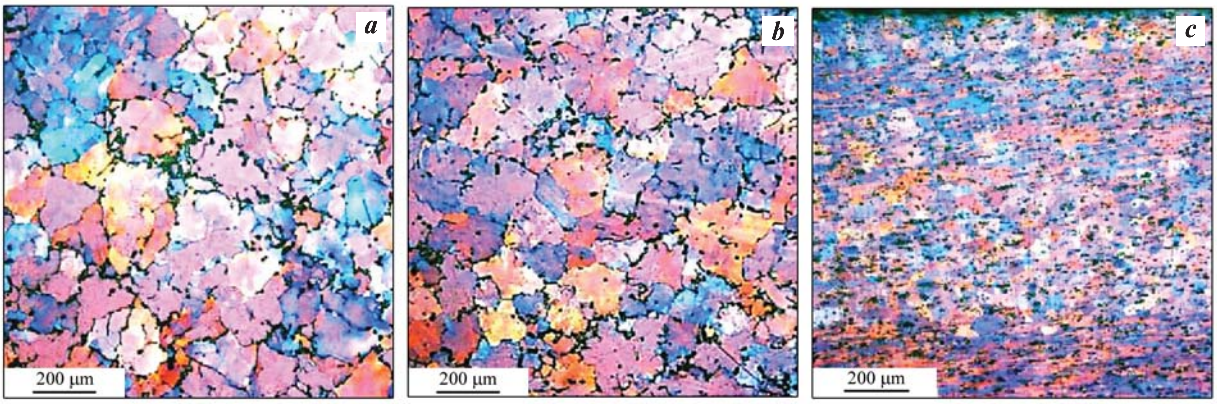


**Fig. 2.** The bar microstructure in polarized light. Bar center (***a***), at half of the radius from the center (***b***), and the circumference (***c***)

**Рис. 2.** Микроструктура в поляризованном свете прутка в центре (***a***), на половине радиуса (***b***) и на периферии (***c***)

circumference (6× difference). It indicates inconsistent penetration of the strains along the radius. The smaller the grain size, the larger the strain.

Fig. 3 shows the strength vs. temperature curve. There is a large (up to 94 %) difference between the ultimate tensile strength and offset yield strength at room temperature. However, it drops sharply at $t$ = = 300 °C. The strength decreases as the temperature increases.

The comparison was made for the measured strength values at elevated temperatures to those reported by other researchers. Chinese researchers [18] performed static tests (0.001 $s^{-1}$ strain rate) with the 6061 alloy at $t$ = 450 °C. The yield stress was 18 MPa. This value is similar to the yield offset measured with the procedure proposed by A.V. Tretiakov and V.I. Zyuzin [19]. The tested material strength almost doubled, thus indicating its incomplete softening. The authors of the paper [18] suggested that the softening in the temperature range which they studied is caused not by recrystallization, but by dynamic recovery.

Fig. 4 shows the ductility properties of the alloy. This relationship is non-monotonic in contrast to strength. The test values was compared to the available results for the AD33 alloy. For example, according to matweb.com, alloy 6061 (AD33 analog made to the ASTM standard) after annealing has 124 MPa tensile strength and

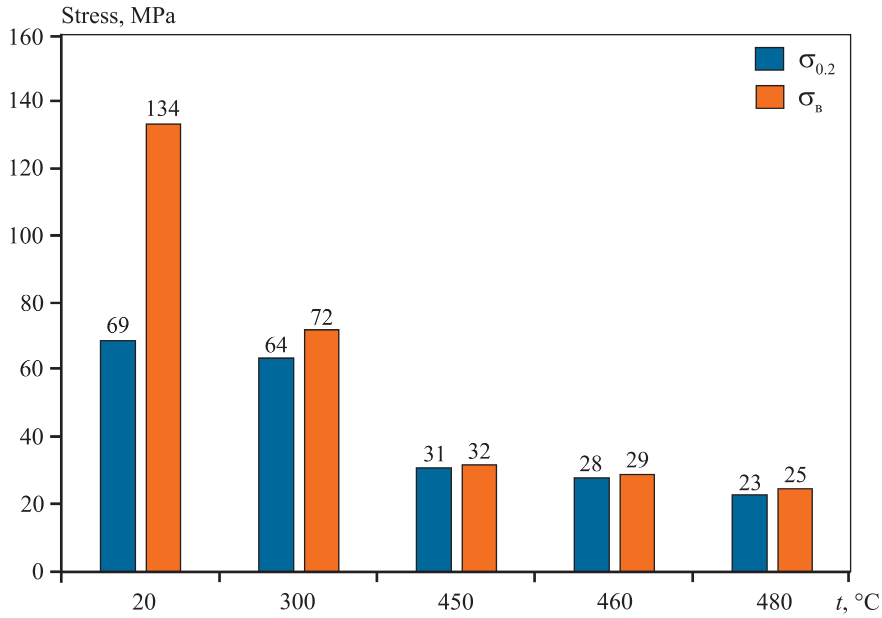


**Fig. 3.** Strength vs. test temperature curve

**Рис. 3.** Зависимость прочностных свойств от температуры испытаний

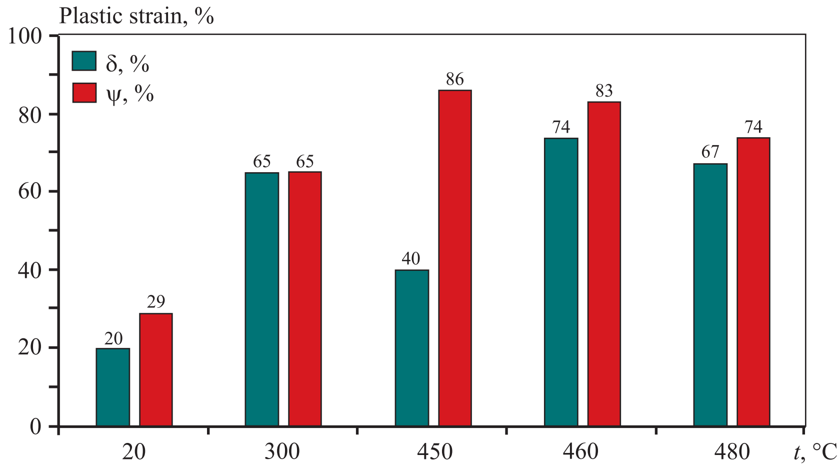


**Fig. 4.** The bar front end ductility vs. test temperature

**Рис. 4.** Показатели пластичности передней части прутка в зависимости от температуры испытаний

55 MPa yield strength. The experimental values were 134 and 69 MPa (8 % and 25 % higher), respectively, i.e. the strength exceeded the standard values for the annealed alloy.

The matweb.com database indicates the relative elongation at break for the alloy is 30 %. The relative elongation at break that we measured is 19 %, which is less than the rated value by $100 \cdot (30 - 19)/30 \approx 37$ %. This means that the bar front end after extrusion is partially hardened. The hardening is more intense at the circumference. It is confirmed by greater grain refinement among other things.

The relative reduction of area can be used to estimate the shear strain at break and to plot the fracture diagram [20].

Fig. 4 shows that the relative reduction of area increases sharply as the metal is heated: at $t = 300$ °C it is 65 % and remains high (74—86 %) at 450—480 °C. This enables the subsequent metal forming without cracking. It is assumed that the extruded bar front end will be re-extruded at the next process stage. The high strain during extrusion will further enhance the metal structure to its final form.

## Simulation

The above conclusion can be confirmed by simulation of the metal behavior during extrusion with a small area reduction. DEFORM-2D software was used. The stress-strain simulation model was axisymmetric. The thermal boundary conditions were as close as possible to the actual values:

— bar temperature: 470 °C;
— press container temperature: 450 °C;
— die and pressure pad temperature: 380 °C;
— ambient temperature at the die hole: 20 °C;
— convective heat transfer coefficient: 0.02 N/s/mm/°C;
— overall heat transfer coefficient: 11 N/c/mm/°C.

The coefficient values and UoMs are as indicated in the software UI.

The extrusion ram velocity was 3.7 mm/s. The boundary conditions are expressed as Siebel law for the 0.7 friction coefficient. The reason for this is the high normal stress typical of extrusion. The container and die diameters were 800 mm and 355.6 mm, respectively, identical to the industrial test (see above). The more detailed problem statement is presented in [21].

Fig. 5 shows the simulation results as equal strain regions. Indeed, the metal at the circumference is exposed to a greater strain degree from the beginning of extrusion. This is because the bar front end is extruded first as an undeformed, rigid plug with a diameter equal to the die diameter. Then the strain rate increases inwards. This process is gradual and slow.

Fig. 5, *a*—*d* shows the steps of this sequence and the color strain scale (Fig. 5, *e*)

In the first step (Fig. 5, *a*), the strain is localized near the die. In the second step (Fig. 5, *d*), a “dead” (rigid) area is formed in the vicinity of the die/container liner interface. The circumference metal layer with a 1.75—2.00 reduction of area is formed. Concurrently, this range is 0.75—1.00 (half of the circumference value) at the bar center.

In the third step (Fig. 5, *c*), the circumference layer with an elevated strain has a wedge-like shape. Its thickness is increased, i.e., the process is not yet at the steady phase. The extruded length-to-bar diameter ratio is 2. In

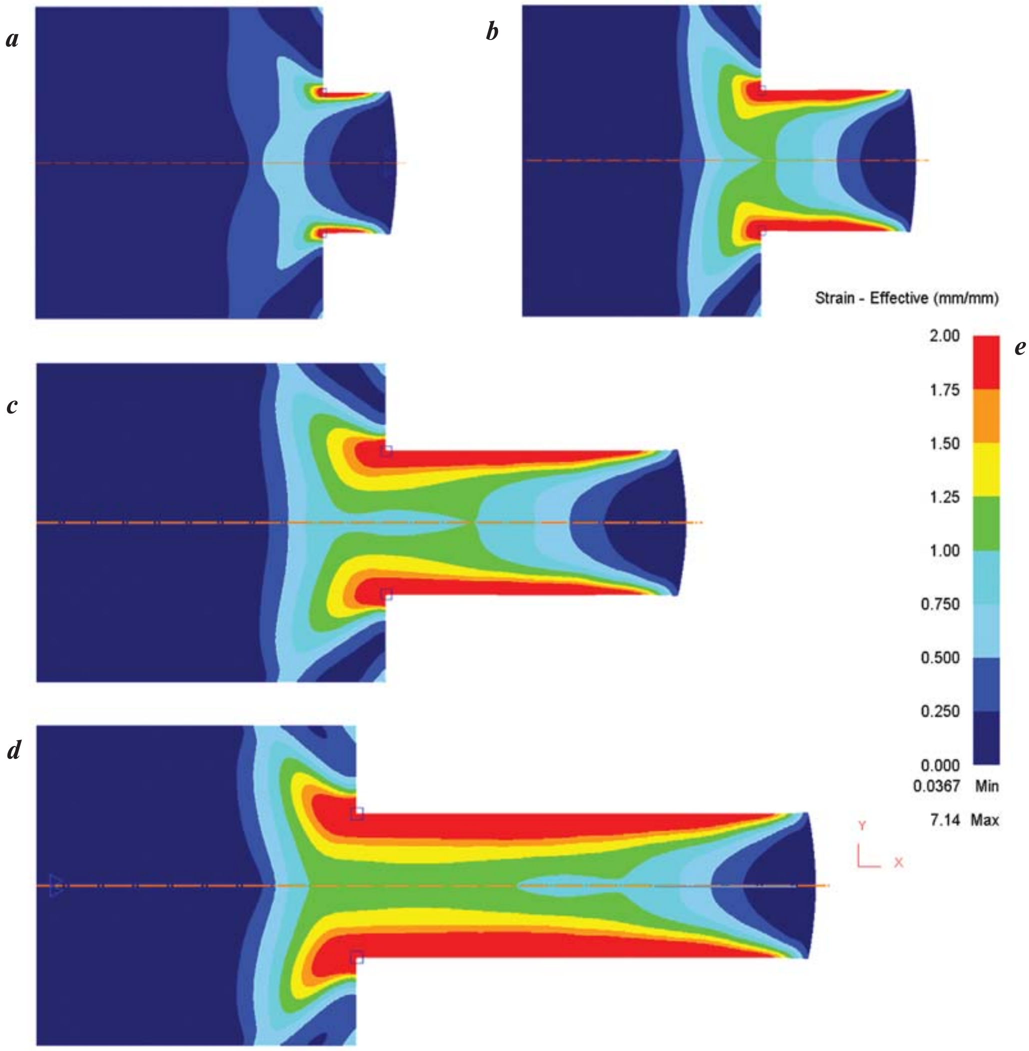


**Fig. 5.** Strain distribution vs. the bar front end relative extruded length (length to diameter ratio)
***a*** – 0.5, ***b*** – 1.0, ***c*** – 2.0, ***d*** – 3.0, ***e*** – effective strain color scale

**Рис. 5.** Изменение картины распределения степени деформации по мере выдавливания переднего конца прутка на относительную длину (отношение его длины к диаметру)
***а*** – 0,5, ***б*** – 1,0, ***в*** – 2,0, ***г*** – 3,0, ***д*** – цветовая шкала степени деформации strain effective

the fourth step, the circumference layer (with elevated strain) has an equal thickness along the extrusion axis. It indicates the steady phase. The strain in the center is now in the 1.00—1.25 range.

The estimated strain as the logarithm of the reduction ratio (the logarithm of the bar area before/after extrusion ratio) is 0.7. The FEM analysis gives slightly excessive strain values, since the shear strain is also included, but the reduction ratio is ignored.

In general, the color-coded strain patterns show that at the steady phase. The plastic strain at the bar front end is higher at the circumference than in the center [22]. It confirms the above structural analysis results. They show that the bar central part may retain its cast structure, while the circumference is deformed.

If the bar central part is required to have some specific properties, the bar has to undergo another manufacturing operation to increase the accumulated strain.

## Conclusion

The structural analysis of the hot-pressed 6061 aluminum alloy bar front end showed that the front end has an inconsistent grain size distribution. The central part contains large grains. The grain size decreases towards the circumference.

The hot sample tests revealed a sufficiently high ductility of the extruded bar front end. The bar is suitable for re-extrusion to process the areas insufficiently deformed during the first extrusion.

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