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May, 28-29, 2019, Ternopil, Ukraine

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Edited by:
Petro Yasniy, František Duchoň, Pavlo Maruschak, Oleg Lyashuk

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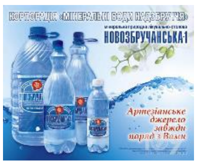

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Characteristics and thermomechanical modes of aluminum alloys hot deformation

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Abstract: The widespread use of aluminum alloys is determined by their technical, physical and mechanical properties. The purpose of this paper is to present the characteristics of thermomechanical models of aluminum alloys hot deformation and to explain how they impact the properties of the these alloys. The application of the workpiece rolling process under the conditions of isothermal deformation makes it possible to maximize the effect of ductility. The deformation of hot workpieces is done by the tool heated to the same temperature (or close to them). Such a scheme of hot deformation will reduce the effort by increasing the ductility of the treated metal which occurs due to the full course of stabilizing processes. Uniform deformation of the workpiece provides a good and comprehensive reconstruction of the structure, in the absence of complicated deformation zones and local overheating. And, as a result, it reduces the dispersion of properties in the workpiece volume. It was established that workpieces rolling in conditions of isothermal deformation are reduced the of metal pressure on a roll in 1.8 times or even more.

Keywords: aluminum alloys, hot deformation, ductility.

1. Introduction

Aluminum alloys are widely used in automobile engineering, shipbuilding, aircraft engineering. The most widespread use of aluminum alloys has been found in aviation (60-70%) and is currently one of the main structural materials in the aviation engineering. In the future wider use of aluminum and its alloys in automobile engineering is not excluded. Today, most cars of the Japanese brands such as Mazda, Mitsubishi use aluminum alloys in their designs. This is due to the sufficient strength of the alloys, good welding, which provides the ability to receive high-strength welded structures. The high corrosion resistance allows to reduce costs of surface treatment. Lightness reduces the specific energy consumption on a car's drive. The use of aluminum parts in modern cars allows to reduce the total weight of the car by 25-30%, which reduces the fuel consumption accordingly. The use of aluminum alloys in automotive industry facilitates technological operations of production of details as some aluminum alloys are easily deformed, others have good casting properties. This provides the manufacture of complex sections parts, which on indicators of stiffness do not concede steel. The ductility properties of aluminum provide a reduction in the level of vibration of the body in the process of motion of the car by uneven roads.

To aluminum alloys used in automotive engineering impose a certain complex of requirements: they must have high static strength properties (strength limit, yield strength, cut resistance),

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satisfactory ductility and thermomechanical characteristics which must be taken into account when developing technological processes of their hot deformation.

Technological properties of allows provide mass production of semi-finished products from aluminum alloys at metallurgical plants and comparatively easy parts treatment.

The structure and properties of products made of aluminum alloys are mainly determined by the method of their production, which is divided into two main groups: deformable – treatment by pressure (production of sheets, plates, profiles, forgings, stampings, pipes, etc.); foundry – production of shaped castings.

2. Literature review

The deformation behavior of a 2024 aluminum alloy sheet at elevated temperatures was studied by uniaxial hot tensile tests over the nominal initial strain rate range of 0.001-0.1 s(-1) and temperature range of 375-450 degrees C, in order to analyze the deformation behavior with higher accuracy, a Digital Image Correlation (DIC) system was applied to determine the strain distribution during hot tensile tests [1].

High cycle fatigue properties of 2124 aluminum alloy plates with different thickness were investigated by determining fatigue S–N curves, fatigue crack growth rates and fracture toughness of 2124-T851 aluminum alloy plates with the thickness of 30mm, 40mm and 55mm, respectively [2].

Hot torsion tests were carried out on an AA6005 modified with CaO-added Mg to study its hot deformation behavior. The flow curves indicated that the failure strain of the modified alloy was greater than that of the conventional alloy at low temperature and all strain rates employed in this study [3].

To characterize the hot deformation behavior of commonly used aluminum alloy, a homogeneous Al-Mg-Si-Mn-Cr alloy was analyzed by thermal simulation test at deformation temperature range of 653-803K and strain rate range of 0.01-10s(-1) [4,10].

A modified powder hot extrusion including gas atomization, pre-compaction and hot extrusion was used to fabricate an ultrahigh strength Al-Zn-Mg-Cu-Zr-Sc (7055) alloy, the results reveal that a homogeneous microstructure containing fine grains and tiny second phases is formed after extrusion [5].

The effect of increasing pre-stretching to higher levels, than are currently used in industrial practice, has been investigated on the strength, microstructure, and precipitation kinetics seen during artificial ageing an Al-Cu-Li alloy AA2195 - focussing on the behaviour of the main [6].

The inhomogeneous deformation which appears in hot rough rolling of aluminum alloy plate, reduces rolling output and negatively affects the rolling process, to study the formation mechanism of the inhomogeneous deformation, a finite element model for the five-pass hot rough rolling process of aluminum alloy plate is built [7].

In this paper different thermo-mechanical treatments were performed on the commercial aluminum alloy 2024-T3, in order to improve deformation characteristics, these treatments include the solution heat treatments of precipitates that have been performed at the temperature of 500 degrees C for 4, 6 and 8 hours followed by a quenching in water, hot and cold rolling, recrystallization [8].

Hot deformation in 6063 aluminum alloys was investigated by hot compression testing over the temperature range of 573-723 K with strain rates of 0.01-10 s(-1) using a Gleeble 3500 thermal-mechanical simulator [9].

The dynamic recrystallization behavior of 7085 aluminum alloy during hot compression at various temperatures (573-723 K) and strain rates (0.01-10 s(-1)) was studied by Electron Back Scattered Diffraction (EBSD), Electro-Probe Microanalyzer (EPMA) and Transmission Electron Microscopy (TEM) [10].

3. Research methods

Research methods. Now there are not enough works on a research of possible of workpiece rolling in isothermal deformation and close to this process one. Therefore, carrying out researches on influence of workpiece heating temperatures and rolling stamps, deformation degree on the process parameters of workpiece rolling in the conditions of isothermal and deformation close to it is a relevant task. The solution of this problem can lead to improvement of ductility and decrease in efforts of deformation, improvement of quality of semi-finished products.

The theoretical researches of the process of a current of metal in transitional and constant zones when workpiece rolling in a deformation source at volume deformation which is done taking into account the development of deformation in time, application of an imaginary coordinate grid, finite differences and variable parameter of elasticity.

The methods of coordinate grid, strain gauging, optical and electron microscopy, X-ray microanalysis, mathematical statistics are used in experimental research.

The hot deformation behavior of the homogenized Al-3.2Mg-0.4Er aluminum alloy was investigated at 573-723 K under strain rates of 0.001-1 s(-1), on the basis of compression experimental results, an accurate phenomenological constitutive equation that coupled the effects of strain rate, deformation temperature and strain was modeled [11].

Previous studies have demonstrated that the static softening kinetics of 7150 aluminum alloy showed typical sigmoidal behavior at 400 degrees C and softening plateaus at 300 degrees C, in present work, the static softening mechanisms, the microstructural evolution during post-deformation holding was studied by optical microscopy, scanning electron microscope, electron back-scattered diffraction and transmission electron microscopy [12].

4. Discussion

The features of the structure depend on the technology of semi-finished products, which includes: the duration of heating and the temperature of deformation; circuits, degrees, rates and duration of deformation. For example, the technology of sheet production is very different from the technology of production of stamping or profiles. Deformed semi-finished products (sheets, profiles, stamping, etc.), obtained from one alloy can vary significantly in mechanical and other properties after identical final heat treatment.

Typically, the properties of aluminum alloys are considered depending on the chemical composition and the mode of final heat treatment. Due to that, these factors determine the important structural parameters on which properties depend the concentration of the main alloying components in the solid solution, as well as the structure and size of the phases are separated from solid solution during heat treatment (annealing or aging) such approach to assessment of properties of alloys is optimal.

Aluminum alloys in the aviation industry are one of the main structural materials and are used mainly in a deformed state, which provides increased characteristics and reliability in operation.

Aluminum deformable alloys, with the possibility of pressures treatment in the heated state are conditionally divided into alloys of high, medium and reduced technological ductility [13].

In the paper [14] it is given aluminum alloys which are widely used for hot deformation (Table 1).

Table 1. Nomenclature of aluminum alloys for the production of forgings and stamping

Alloy Grade	Alloys System
Thermally not strengthened alloys	
AMg2, AMg3 AMg5, AMg6	Al-Mg
Thermally strengthened alloys	
D1 D20, D21 B93, B95, B96c AB AK6, AK6-1, AK8 AK4, AK4-1	Al-Cu-Mg Al-Cu Al-Zn-Mg-Cu Al-Mg-Si Al-Cu-Mg-Si Al-Cu-Mg-Si-Ni-Fe

Alloys that have high technological ductility are: AMC; AMg1; AMg2; AMg3; AD31; AD33; AD35; AB; AK6; 01205; ADO; АД1.

Middle technological ductility has alloys: D1; D1ч; D19ch; BAD1; BD17; D20; D21; 1201; AMg4; AMg5: AMg5p; AMg6: B92; B92c; B93pch; B95; B95pch; B96ch; 01963; 1913; 1230; 1915; M40; Ak4; Ak4-1; Ak4-1ch; Ak8; D16ch.

Reduced technological ductility is characteristic of powder materials such as: SAP1(1019); SAP2(1029); SAP3(1039); SAS1-400(1319).

The proposed classification of aluminum alloys for strength and ductility is given by the authors in the paper [15] (Table 2).

Table 2. Classification according to the strength of aluminum and alloys on its basis

Group	Strength and Ductility	Alloys	Mechanical Properties	
			$\sigma_в$ kg / mm^2	δ, %
I	Soft, ductility	AD, AB, AMC, Mg1, AMg2, D31, AD33	Less 30	5-22
II	Medium strength and ductility	D1, AK2, AK4, AK4-1, AK6, AK6-1, BD17, AMg6	30-45	10-15
III	High strength with reduced technological properties	AK8, B98, B95, B96, BAD23	More 45	5

Significant influence on the ductility, mechanical properties and structure of the finished forging parets and stamps is provided by deformation modes such as temperature, rates and degree of deformation. Thermomechanical deformation modes should provide sufficient ductility, similar structure and high mechanical properties.

In the papers [13,16].the technical conditions and thermomechanical modes of deformation of aluminum alloys are given to ensure of these requirements (Table 3).

Table 3. Thermomechanical modes of forging and stamping of aluminum alloys

Alloy Grade	Temperature interval of deformation, ºC	Admissible degree of deformation %		Used forge equipment
		Casting workpiece	Pressed workpiece	
AMn, AMg1, AMg2,AB, AD31, AD33, AD35, AK6, AD0, AD1, 01205	470-300 470-300	70 70	90 90	Hydraulic press Hammer or mechanical press
D1, D1ch, BD17, 1230, AK8	470-370 450-350	60 -	70 60	Hydraulic press Hammer or mechanical press
D20, D21, 1201, AK4, AK4-1, AK4-1ч	470-350 430-320	60 -	70 60	Hydraulic press Hammer or mechanical press
AMg3,AMg4, AMg5, AMg5p, AMg6, B92,	430-320	60	60	Hydraulic press
M40, B92c, 1915, 1913	430-300	-	50	Hammer or mechanical press
B95, B95pch, B96C, B96Cpch, B96C3	430-350 430-320	60 -	60 50	Hydraulic press Hammer or mechanical press
D19ch, BAD1 (1191), D16ch	470-350 430-350	60 -	60 50	Hydraulic press Hammer or mechanical press

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From the practical point of view, in the paper [13] it is recommended: "At the deformation of workpieces in the direction perpendicular to an axis (on forming), the value of tolerable deformation which are given in Table 3, have to be reduced for aluminum alloys by 15 - 25%". In order to avoid the formation of a coarse-grained structure, in the course of the ongoing processes of recrystallization, forging and stamping of aluminum alloys, we recommend carry them out with a deformation not less than 15 - 20% in one heating.

In the paper [16] it is noted that "Alloys of reduced strength (σ_B less than 30 kg / mm2), Table 2, as well as the medium strength alloy Aк6 have high ductility, which practically does not depend on the strain rates. Alloys of medium strength (σ_B= 30 – 45 kg / mm2) and high strength (σ_B> 45 kg / mm2) have good ductility», but with the increase in the rates of application of the deformation force from static (up to 0.3 m / s) to dynamic (up to 8.0 m / s), the ductility of these alloys is reduced by 15-20%, which should be taken into account when treatment them on mechanical presses and hammers.

In the paper [5], it was noted that aluminum alloys are less technologically advanced for hot deformation than steel. As relative lengthening δ, the index of ductility, at the forging temperatures in aluminum alloys is lower. Also, the physical and mechanical and thermomechanical properties of their hot deformation are different.

For carrying out experiments, production of stamped forgings from aluminum alloys of the lowered technological plasticity from powder materials SAP1, SAP2, SAP3, SaS1 - 400, will not be considered.

We consider alloys of high technological ductility - AMC, AMg1, AMg2, AMg3, AK6 and alloys of the average technological plasticity - AMg4, AMg5, AMg6, AK4, AK4 - 1, AK8.

The concept of "coefficient of technological ductility" is introduced in order to determine the technology of a particular alloy, which is defined from the following expression:

$$K = (\sigma^{K}_{v} - \sigma^{n}_{v})/(t^{\circ}_{n} - t^{\circ}_{\kappa}) = \Delta\sigma_{B}/\Delta t^{\circ} \qquad (1)$$

Where σ^{K}_{v}, σ^{n}_{v} - temporal resistance at the temperature of the beginning and end of the deformation, t°_{n} i t°_{κ} - the temperatures of the beginning and end of the deformation.

Taking into account that the relative lengthening of **δ,** as the index of ductility, at forging temperatures in aluminum alloys is lower than in steel., We can conclude that aluminum alloys are less technologically advanced for hot deformation as their coefficient C is higher than other equal conditions. This is confirmed by the analysis of data presented in Table 4, 5.

Table 4. Thermomechanical characteristics of aluminum alloys and steel

Material	σ_v, MPa			δ, %			ε_{max}, %		
	Temperature °C								
	400	450	500	400	450	500	400	450	500
	Aluminum alloys								
B93	78.5	39.2	29.4	54.0	63.0	74.0	62.0	55.0	40.0
AK4-1	49.0	39.2	19.6	50.0	60.0	44.0	60.0	60.0	50.0
AK8	39.2	31.4	24.5	40.0	35.0	30.0	72.0	72.0	72.0
	Temperature °C								
	1000	1100	1200	1000	1100	1200	1000	1100	1200
	Steel								
20	49.0	39.2	29.4	63.0	59.0	64.0	91.0	92.0	93.0
45	49.0	39.2	29.4	53.0	63.0	64.0	90.0	91.0	92.0
30HGSA	29.4	19.6	9.8	30.0	56.0	60.0	-	-	-

Besides, when developing technological process of production of stamped forgings of aluminum alloys, it is necessary to consider features of hot deformation of the aluminum alloys which are given in the paper [17] and include:

1. Lower ability of defect-free filling of deep cavities of the die by subsidence, than extrusion. This is explained by the deformation scheme during subsidence, in which a significant tensile stress appears, and the deformation scheme during extrusion reduces them to a minimum.

Table 5. The value of the coefficient of technological ductility for a number of aluminum alloys and steel

Alloys	Deformation temperature ° C		Temporal resistance, σ_v, MPa, at deformation temperature, C		Coefficient of technological ductility, C.	Scope angle α
	beginning	end	beginning	end		
AMg6	430	320	58.9	88.3	0.027	1°30′
AD31	470	350	24.5	58.9	0.029	1°40′
АК4	470	350	24.5	58.9	0.029	1°40′
AMg	470	350	39.2	78.5	0.033	1°00′
B95	400	320	58.9	88.3	0.037	2°10′
АК6	470	350	29.4	78.5	0.041	2°20′
B93	430	350	49.0	9.8	0.062	3°30′
BD17	450	380	58.9	9.8	0.057	3°20′
Sт.20	1250	800	19.6	78.5	0.019	1°10′
20H	1200	800	9.8	49.0	0.010	0°40′
30HGSA	1140	830	24.5	68.7	0.014	0°45′
H18n9t	1150	900	29.4	78.5	0.020	1°10′
U7a	1100	850	29.4	83.5	0.022	1°15′
R18	1150	920	24.5	9.8	0.032	1°50′

2. Rather narrow temperature interval of hot deformation which are for various alloys from 80 to 170°C (Table 3).

3. The top limit of deformation temperature interval of the thermo-strengthening alloys is close to upper the permissible temperature limit of heating temperature of alloys at their hardening, therefore strict control of temperature and time of heating of the workpieces is necessary to avoid formation of coarse-grained structure or metal overburning, especially during the heating and deformation of workpieces from low-plastic alloys [18].

4. The high thermal conductivity of aluminum alloys leads to fast decrease in the temperature of the workpieces in a die and the frequent occurrence of "cold" cracks in thin intersections (especially in the line of split stamps) during deformation.

5. The low plasticity of some alloys at deformation temperatures limits the tolerable degree of deformation which leads in some cases to formation of surface cracks and internal delamination in stamped forgings.

6. The small coefficient of drawing and the large expansion coefficient (in comparison with steel) make almost impossible these operations on the stamping equipment when carrying out open stretching.

7. The increased tendency to:

- welding of contact metal layers of the workpiece to the surface of the die engraving at high degrees of deformation, due to low-quality lubrication and chemical activity of aluminum alloys;
- the formation of clamps when filling deep and sufficiently wide cavities and edges due to the relatively large coefficient of friction of the metal on the contact of die figure surfaces. As a result of which the bent of the internal volumes of metal takes place with its deposited layers, which are in contact with the die surface;
- the appearance of folds and clamps at the deformation of pre-bent workpieces in the bending position, as well as during the operation of the open stretching;
- appeared defects of "crack" under edges on stamped forgings, especially at high deformation rates (5-7m/s);

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- appearing of zones with coarse-grained structure on intersections of a stamped forging part after the strengthening operation of heat treatment. The cause of which is unevenness of deformation when stamping. To reduce of these zones formation, requires application of technological passages for metal volumes of initial workpiece redistribution.

At metal deformation by the cold or warmed-up up to the low temperature tool, possibilities of observance of the optimum thermomechanical mode are limited because of workpiece cooling during its carrying and further deformation. At the same time deformation resistance increases that causes the needs of use of more powerful equipment and decrease in ductility of metal. Owing to heterogeneity of the temperature field the unevenness of strength properties on all volume of a deformable body is observed, the wear of the tool is increased. Therefore, when determining the temperature interval of deformation, it is predict the inevitable heat loss by the workpiece during transport passages and in the process of deformation.

The degree of cooling of the workpiece depends on their size and the number of passages during the treatment. That is why an additional heating of the workpieces is introduced with a large number of passages, which increases the cycle of the technological process, reduces the quality of the parts and semi-finished products. To exclude the listed factors, it is often used heating to temperatures that is higher than the nominal treatment temperature during deformation of workpieces under normal conditions. It raises the energy consumption, raises the heating time of the workpieces, and also worsens the structure of the metal, reduces its ductility and strength properties, increases the thickness of the scale, degraded or defective layer on the surface of the workpiece. For example, with an increase in the temperature of the heating of titanium alloys from 960 to 1200°C, the average grain size increases from 0.06 to 0.8mm, and the thickness of the alfied layer also grows rapidly: 0.005mm at 850°C and 5 minutes; 0,025mm at 950°C; 0,05mm at 1000°C and 0,11mm at 1200°C.

Cooling of the workpiece in contact with the cold tool reduces the plasticity, greatly increases the deformation effort, especially in the manufacture of parts characterized by a large ratio of surface area to volume. Increasing the effort entails the use of more powerful equipment, the quality of forging is reduced because of the elastic deformation of the "equipment - tool" system. When deformed by a cold or slightly heated instrument in the preform, an inhomogeneous temperature field is formed, zones of difficult deformation arise and deformation localization cells appear. Particularly strong is the heterogeneity of the temperature field, when processing titanium alloys, which thermal conductivity is 5-6 times lower than that of steel.

It is especially important to prevent loss of temperature of the workpiece during hot deformation of metals with a narrow temperature interval of deformation.

The effectiveness of hot volumetric deformation can be increased by maintaining the heat of the stamped workpiece, using heat-shielding coatings (asbestos cladding, asbestos hinges of the suspension type, protective coatings on the basis of glass, graphite, etc.) that reduce the loss of heat when transferred from the stove to deforming equipment and in the process of deformation, increasing the temperature of the heating of stamps. When transporting the workpiece from the furnace, in order to maintain the heating temperature, various designs, heat-shielding metal sheaths are also used.

From the traditional methods of hot deformation in the treatment of metals by pressure, the isothermal is characterized by the fact that the shaping of the heated preform is carried out in the tool heated to the deformation temperature, and the temperature of the heated workpiece and deforming tool is maintained constant, close to the upper limit of the melting temperature, throughout the process.

Deformation of metal under isometric and deformation approaches is characterized by an increase in plasticity compared with plasticity when treated in a cold instrument. This is due to the lower rate of deformation, the lower limit of which is limited only by the productivity of the process. As a result, the time "fixing defects", which arises when metal deformation increases, decreases the temperature voltage in the volume of the workpiece, the deformation becomes more even.

Efforts and the work of deformation decrease in the conditions of isometric deformation, also the amount of released heat reduce too as a result of deformation, which is distributed in the volume of the workpiece rather evenly due to homogeneous deformation. This is especially important in the deformation of metals and alloys, the structure of which strongly depends on temperature changes. The uniform deformation of the workpiece in the absence of zones of the complicated deformation and local overheating due to the thermal effect, as a rule, provides a good and comprehensive treatment of the

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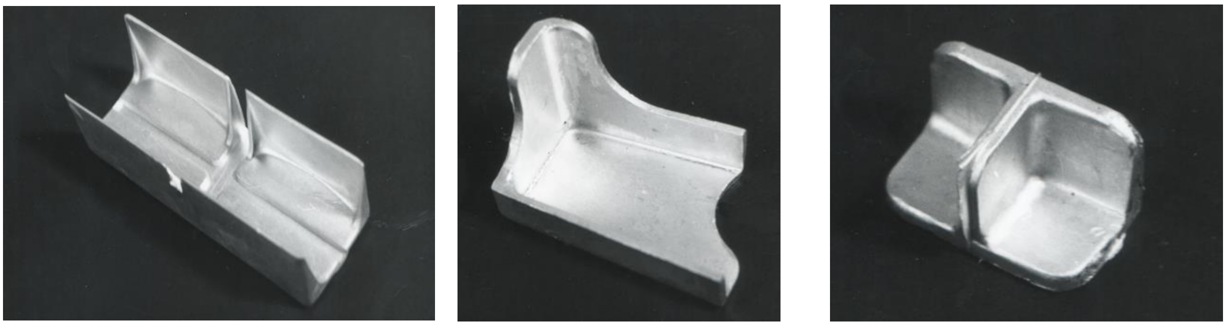
structure, high strength and plastic characteristics of the metal and reduces dispersion of properties in the volume of the workpiece.

Excluding of the workpiece cooling, it is possible to reduce the deformation temperature in comparison with the usual conditions and to process at a temperature close to the upper limit of the temperature interval for this alloy. For example, reduction of temperature of deformation by 50-200°C for titanium alloys facilitates carrying out deformation and provides to get of high-quality parts, reduces depth of an alfire layer.

Creation of conditions of isothermal deformation allows to carry out stampings in the optimum thermomechanical mode, to use superplastic phenomenon and to give the chance to make stamped forgings of a complex configuration (flanges, brackets, fittings, levers, swings, etc.), with minimum assumptions to mechanical treatment, minimal float, stamping scope 30'... 1°30', to provide a coefficient of metal use 0,8...0,85, Fig. 1. a, b, c.



(a) (b) (c)

Figure 1. Typical forging parts made by isothermal stamping

5. Conclusions

The accuracy of parts obtained under isometric deformation increases significantly due to:

- reduction of elastic deformations of the equipment system, since the resistance to deformation of the metal and the processing effort is reduced;

- reduction of deformation temperature fluctuations, which increases the stability of the geometric dimensions of the machined parts;

- reduction of residual stress that reduces deformation during the cooling and heat treatment and improves quality;

- reduction of the thickness of the defective layer and improvement of the quality of the part surface (semi-finished product) as a result of lesser action of the heated metal with the environment when the temperature deformation is reduced and the use of effective protective and lubricating coatings.

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