

Softening of Low-alloyed Titanium Billets with Laser Annealing

Serguei P. Murzin^{1*} and Nikolay L. Kazanskiy^{2,3}

¹Department of Automatic Systems of Power Plants, Samara National Research University, Samara, Russia

²Image Processing Systems Institute of RAS – Branch of the FSRC “Crystallography and Photonics” RAS, Samara, Russia

³Department of Technical Cybernetics, Samara National Research University, Samara, Russia

*Corresponding author: murzin@ssau.ru

Abstract. An experimental study of work-hardened metal release conditions and recrystallized structure formation with laser heating, which showed the possibility of these processes in low-alloy titanium was performed. Studies of treated materials properties showed that using of laser annealing enhances ultimate tensile strain and reduces minimum bend angle for cold deformation of rolled sheet metal parts of these materials. Using of laser annealing for local softening before shaping billets of titanium alloys allows to improve the accuracy of parts manufacturing by reducing their springy action. This provides an opportunity to expand their shaping options without additional heating.

1. Introduction

Laser beam machining is a progressive process for improving of selected materials properties and service characteristics. The feasibility and advantages of the use of lasers in material processing are determined by the possibility of a non-contact, strictly dosed and intense supply of energy to the product surface. Laser technologies can be used to process remote as well as local areas of objects in the absence of vibrations and other negative effects on the material. These and other significant advantages lead to greater potential for the usage laser processing in present time as well as in the future. Due to its extremely localized, concentrated energy input of focused laser radiation, laser material processing delivers a higher energy density as any other heat source to processed components. Thus, laser material treatment can be used not only for laser welding or cutting, but for modification of physical and mechanical properties of materials. Current status of achievements in the area of physical characteristics of laser beam processing is presented in various papers and monographs [1-3]. Numerous reference books [4-6] describe in detail applications of laser devices in diverse production technologies. It is shown that such important characteristics of metallic materials, as tensile strength, fatigue strength and wear resistance are structurally-sensitive, i.e., can be controlled by proper changes of material structures due to laser processing. Only few works are devoted to investigations of softening materials by controlled changes in the structure of these materials [7-10]. Even the term «laser annealing», which in a broader sense means changing the structure of solids by laser radiation of varying duration in the literature usually refers to a pulse oriented crystallization of semiconductor structures by laser radiation of nanosecond duration.



One of the most effective means for increasing the strength of machine parts from sheet and round blanks is to use cold-worked materials which have high hardness and low plasticity. While improving the structural condition of the material by annealing, a significant improvement in the plastic flow of the metal and the localization of the deformation can be realized. [7-9] demonstrated the possibility of alloys recrystallization at high temperatures and short exposure times during laser heating. The width and location of the annealing zone on the blank are determined by the accuracy of forming operations and allowable deformation without fracture. Except the laser, no other known local heating method can be used to obtain the desired width of the processing zone because of their lower power density. In [10] the method of local laser annealing for metallic sheet materials was developed. Conditions for the removal of cold-hardening and formation of recrystallized structure were determined. The method was implemented using a CO₂-laser. In the optical transformation system, the focusing mirror was a diffractive optical element [11-13]. The power density was increased at the periphery of the rectangular-shaped heat source, which was moving at a constant speed. This resulted in uniform thermal conditions across the width of the heat affected zone. The local laser annealing of plastic deformation areas provides an increase in the ultimate elongation, and a decrease in the minimum bend radius.

Titanium alloys are used in forming production of details of aircraft and their engines for the purpose of increase in specific durability and rigidity of products [14, 15]. Medium and high-alloyed titanium alloys practically don't give in to a cold shaping because of the high resistance of metal of deformation, intensive hardening, tendency to cracking and tearing. The parts are manufactured with billets heating using traditional and special techniques at existing stamping production equipment. Billets heating is performed in resistance furnace, radiation and electrocontact heating units, heat conduction equipment [16, 17]. Low- alloyed titanium alloys also have lower ductility characteristics, and because of that the deformed metal should be heated. The most important features that determine processing characteristics of such structural materials, along with limited abilities of cold deformation are their low heat conduction and high interaction activity with the environment. The laser heating is preferred because it enables a significant reduction of metal materials residence time at intense oxidation and surface layers gas saturation temperatures. The purpose of this paper is to determine the possibility of laser annealing using for local softening of low-alloy titanium Ti-2Al-1.5Mn and Ti-4Al-1.5Mn billets before shaping.

2. Material under study and experimental equipment

Titanium alloys Ti-2Al-1.5Mn and Ti-4Al-1.5Mn are related to an alloy group with a prevalence of α -solid solution and a small amount of β -phase (pseudo- α -alloys) and have polymorphic transformation temperature of 1180–1220 K and 1190–1230 K respectively. These alloys are suitable for welded assemblies, parts (including thin-walled) and products continuously operating at temperature up to 570 K, and with operating time up to 2000 hours at temperature of 620 K. Shaping with heating is the main method of low-alloy titanium forming. These alloys have satisfactory technological plasticity at temperature range of 760–870 K for Ti-2Al-1.5Mn and 820–970 K for Ti-4Al-1.5Mn. However, heating in air at temperatures above 770 K forms defective oxide and gas-containing layers on billets surfaces, reducing the parts operational strength and deteriorating the material formability.

One of the main features of laser technologies for processing parts of aircraft engines with adjustable spatial distribution of beam power are increased requirements for the accuracy of maintaining the parameters of processing regimes. This makes it necessary to perform laser processing of parts by continuous radiation in an automatic mode. To provide the required set of characteristics of machined parts in the design of technological processes, it is advisable to apply mathematical modeling methods, it is necessary to modernize the optical system of the process equipment, use a computer control system for the processing of parts and non-destructive express control.

When monitoring temperature fields on the surface of objects, an element base was used from an infrared radiometer-a unit for visualizing the temperature field in the working area of a thermal imager

with analog-to-digital converters, an image input / output unit and a personal computer with the appropriate image processing software. The correspondence of the emissivity of the surface of the investigated object to the values of the level and range of the investigated temperatures was established in the calibration mode of the signal. The temperature distribution over the surface of the object was fixed in the form of an image with different brightness of the sections or in the conventional colors of the RGB palette. Processing of information about thermal processes was carried out using the developed software, functioning in a Windows environment. The analysis of the thermal images was performed both in the automatic mode of operation and in the command interactive mode.

Laser treatment of the parts was performed with CO₂-laser processing equipment BYSTAR 2512 with BTL 1800 laser that has CW output power range 100–1800 W. The beams transport and formation systems including diffractive optical element were used for directive change of the high-intensity laser beam power density distribution [18-21]. The figure 1 shows CO₂-laser processing equipment BYSTAR 2512 with a technological optical device comprising a diffractive optical element and a system for contactless diagnostics of thermal processes.

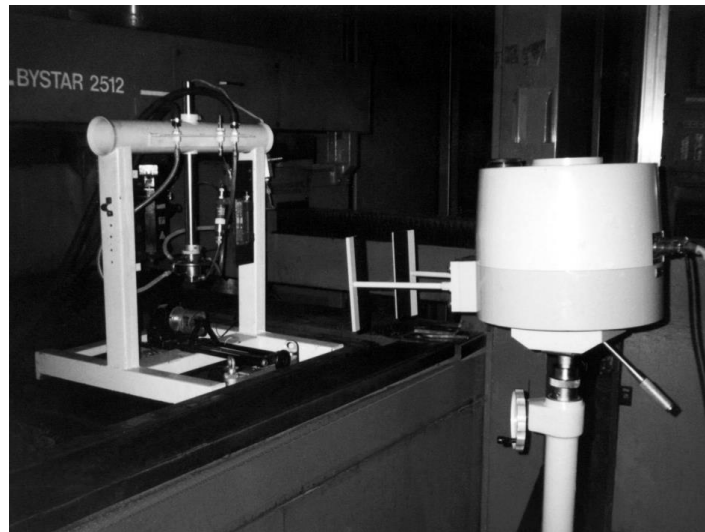


Figure 1. CO₂-laser processing equipment BYSTAR 2512 with a technological optical device comprising a diffractive optical element and a system for contactless diagnostics of thermal processes.

The procedure of mechanical properties testing was conducted using tensile-testing machine Zwick/Roell Z050. The size of the samples was determined in accordance with state standards. A series of stretching tests of rolled sheet Ti-2Al-1.5Mn material specimens with thickness 2 mm were conducted to determine the ultimate tensile strain that characterizes alloys ductility. Rolled sheet titanium alloys samples were tested on bending. The estimation of minimum bend angle was carried out on test stand with force of 200 kN, by continuous increasing the load on the sample until first crack. The support bending radius was 15 mm and rounding mandrel diameter was 6 mm for plates of Ti-2Al-1.5Mn and Ti-4Al-1.5Mn with thickness of 2 mm.

3. Results and discussion

The experimental study of work-hardened metal removal and recrystallized structure formation conditions with laser heating showed the possibility of these processes in low-alloy titanium recrystallization temperature range (for Ti-2Al-1.5Mn: 990–1110 K, and for Ti-4Al-1.5Mn: 1030–1130 K). A nonlinear heat conduction problem was considered in order to determine treatment parameters during heating of the sample with surface heat source. The calculation was made for the sample that is moving at a constant linear velocity in the three dimensional Cartesian coordinate system placed at the heat source center. The assumption was made that the heat source with specified geometry and spatial power distribution is surface source and occupies an area on the sample.

Nonlinear conditions of heat transfer with the environment were specified on the rest of the surface. The treatment parameters were set as follows: laser power 450 ± 5 W; processing speed 0.6 ± 0.01 m/s.

Figure 2 shows the structure of low-alloy Ti-2Al-1.5Mn rolled sheet titanium with thickness 2 mm after laser annealing. The initial material has a fibrous structure. The annealing zone has a granular structure represented by α -phase and a small amount of β -phase. Recrystallization of deformed structure followed by stable recrystallized structure formation occur during laser annealing.

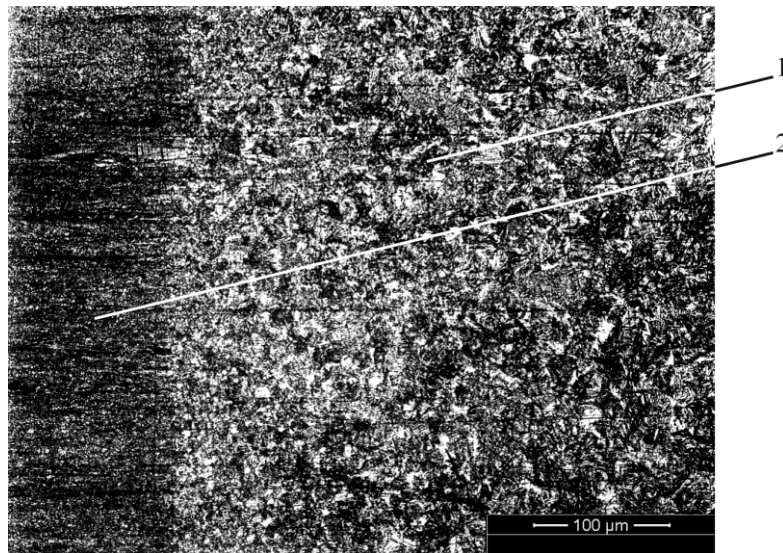


Figure 2. The rolled sheet titanium alloy Ti-2Al-1.5Mn structure after laser annealing: 1 - annealing zone, 2 - initial structure.

The results of stretching tests are shown in table 1. The results of bending tests are presented in table 2. Thus, laser annealing enhances ultimate tensile strain and reduces minimum bend angle for cold deformation of rolled sheet metal parts of these materials, that provides an opportunity to expand their shaping options without additional heating.

Table 1. Stretching tests results for Ti-2Al-1.5Mn rolled sheet material

Material condition	Elongation after fracture, %	Uncertainty of the result, %	Enhance of ultimate tensile strain, %
Before laser annealing	8.2 (7.4–8.9)	7.0	-
After laser annealing	21.5 (18.5–23.5)	7.3	10–15

Table 2. Bending tests results for Ti-2Al-1.5Mn and Ti-4Al-1.5Mn titanium alloys rolled sheet samples of 2mm thickness

Material condition	Minimum bend angle, rad	Uncertainty of the result, %	Reduction of the minimum bend angle, %
Before laser annealing	Ti-2Al-1.5Mn 0.94 (0.9 ... 0.97)	7.6	-
	Ti-4Al-1.5Mn 0.77 (0.73 ... 0.81)	6.8	
After laser annealing	Ti-2Al-1.5Mn 0.6 (0.56 ... 0.64)	5.1	30–40
	Ti-4Al-1.5Mn 0.51 (0.47 ... 0.53)	6.2	30–40

Stamped parts precision depends on a vast number of factors that cause error formation. These factors include: stamp type and billet fixing method, stamp manufacturing precision and its wear, the

technological process structure, i.e. the number and sequence of operations, which quantity increase raises the accumulation of errors, etc. When bending accuracy is heavily dependent on the elastic and plastic material properties, determining the amount of elastic deformations (elastic springing expressed in angular coordinates) and causes manufactured parts forms and dimensions errors.

Comparative tests of Ti-2Al-1.5Mn parts with thickness 2 mm and bending angle 1.04 rad were conducted to estimate springing angle. The prototypes were manufactured with a local laser annealing of bending space in accordance with the developed approach. Control samples were made with same party material, their bending was carried out with the core technology without laser annealing. As a result, the springing angle without laser annealing of bending space was ~ 0.052 rad, with a local laser annealing was 0.028 (0.026–0.03) rad. The use of a local laser annealing reduces the springing angle after bending low-alloy titanium parts by 40–50%. The comparison of laser annealed parts fatigue strength was conducted. The tests were carried out for the first oscillation mode of cantilever fitted parts using step loading at temperature 293 K with the number of test cycles $5 \cdot 10^6$. The comparison showed that the sample parts made using laser annealing are highly competitive with the serial ones.

Thus, using of laser annealing for local softening before shaping billets of titanium alloys allows to improve the accuracy of parts manufacturing by reducing their springy action. Interoperational annealing for work-hardened material removal of alloys having a low critical strain rate is also advisable to be carried out with laser heating. Annealing zone width of the billet and its placing is determined by shaping operations accuracy and conditions of failure strain course. The desired treatment zone width cannot be obtained by any other method except local laser heating as they have no high energy density for heat transfer.

Presumably, the annealing zone formation of a variable width will allow stamping parts with variable bending angle. Combining laser cutting and shaping operations with technological operation of local laser heating is a promising application for specialized equipment. Schemes of stress and strain conditions are different for various shaping operations, but the suggested approach to the development of the combined manufacturing method for laser annealing and stamping operations can be extended to drawing, swaging, flaring, shaping operations, etc. Titanium alloys are used for axial compressors rotor blades manufacture for gas turbine engines. It is known that the equiaxed globular structure of titanium alloy ensures maximum durability, while the needle-type structure ensures maximum heat resistance. Creating structures on local sites of the parts depending on their purpose and operational conditions may be an additional opportunity to increase the reliability of products.

4. Conclusions

The experimental study of work-hardened metal removal conditions and recrystallized structure formation with laser heating, which showed the possibility of these processes in recrystallization temperature range (for Ti-2Al-1.5Mn: 990–1110 K, and for Ti-4Al-1.5Mn: 1030–1130 K) was conducted. The treatment parameters were set as follows: laser power 450 ± 5 W; processing speed 0.6 ± 0.01 m/s. The annealing zone has a granular structure represented by α -phase and a small amount of β -phase. Recrystallization of deformed structure followed by stable recrystallized structure formation occurs during laser annealing.

Using of laser annealing enhances ultimate tensile strain by 10–15% and reduces minimum bend angle by 30–40 % for cold deformation of Ti-4Al-1.5Mn and Ti-2Al-1.5Mn titanium alloys rolled sheet parts. The use of a local laser annealing reduces the springing angle during bending parts of the low-alloy titanium by 40–50%. This provides an opportunity to expand their shaping options without additional heating.

Titanium alloys are used to manufacture working blades of axial compressors of gas turbine engines. It is known that the equiaxial globular structure of titanium alloys provides maximum endurance, and the structure of needle type - maximum heat resistance. The creation of structures depending on the purpose and working conditions of the parts can be an additional reserve to increase their reliability.

Acknowledgments

This work was supported by the Ministry of Education and Science of the Russian Federation as part of the Program "Research and development on priority directions of scientific-technological complex of Russia for 2014-2020" within the project RFMEFI57815X0131.

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