Fracture of light alloys with structured surface layers under dynamic loadings

V.A. Skripnyak[1a], E.G. Skripnyak[1], N.V. Skripnyak[1], L.W. Meyer[2,a], and N. Herzig[2,b]

[1]Tomsk State University, Department of Mechanics of Solids,

36 Lenin Avenue, Tomsk, Russia, 634050,

[2] Nordmetall GmbH, Haupstrasse 16, 09221 Adorf/Erzgebirge, Germany

[1]skrp@ftf.tsu.ru, [2a] lothar.meyer@nordmetall.netl, [2b]norman.herzig@nordmetall.netl

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Abstract. Results of researches testify about influence of the grain sizes on resistance to dynamic fracture of metals and alloys. It is noticed that values of spall strength of some ultrafine-grained aluminium alloys, titanium alloys, and copper exceed values of corresponding coarse grained samples. In this work we present results of researches of deformation and fracture of aluminium and magnesium alloys with the nanostructured surface layers at a quasistatic and dynamic loading. The nanostructured surface layers on the specimens were created by surface mechanical attrition treatment. It was revealed that the structured surface layer influences evolution of shear bands in the volume of metal specimens at high velocity tension. The flow stress increasing of the aluminium and magnesium alloys after surface mechanical attrition treatment is connected with a formation delay on mesoscale levels of meso-shear bands and mesoscale damages. Failure of the alloys occurs by shear failure under approximately 45° of inclination. Similar failure behavior was observed under dynamic loading. Shear bands and shear crack nucleation and growth were observed by high-speed photography. Examination of fracture surfaces in the specimens show increasing of the fractal dimension under dynamic loadings. Under dynamic loading specimens of material with the structured surface layers display a notable decrease in ductility compared to the initial material, where at quasi-static loadings ductility and compressive strength increased.

Introduction

In recent years a new concept called surface nanocrystallization was proposed [1]. It the frameworks of this concept were developed methods of a surface severe plastic deformation (SSPD). A number of these methods named severe surface mechanical treatment (SMAT) posses to create a thin nanostructured layers on the surface of metal sheets and component parts [2,3]. Recently it was shown that nanostructured surface layers can be created on metallic materials such as: aluminum alloy 7075 [4], magnesium alloy AZ91D [5,6], titanium alloys [7,8], Armco-iron, copper, and AISI 304 stainless steel [1]. Materials after SMAT increased the surface hardness, fatigue strength, tribological properties, and chemical and corrosion resistance in comparison of bulk materials. The most important effects of SMAT were obtained on light alloys based on titanium, aluminum, and magnesium. But the mechanical behavior of light alloys after SMAT in wide range of loading condition is poor investigated. In this research we study the influence of SMAT on fracture resistance of typical FCC and HCP metal alloys at quasistatic and dynamic loadings.

The basic scientific problem is connected with creation of theoretical prediction methods of the fracture resistance of alloys and influence of surface roughness after SMAT on inelastic strain before fracture of light alloys. Results of this research can be used for development of computer simulation model of mechanical behavior of component parts after SMAT [9].

Materials.

Samples for investigations have been manufactured of aluminum alloys AMg6, AD-1, a magnesium alloy Ma2-1 and a titanium alloy VT5-1. The AMg6 aluminum alloy was a bar of 60 mm diameter with chemical composition (mass fraction, %) of 0,351 Fe, 0,310 Si, 5,977 Mn, 0,0843 Ti, 0,086 Cu, 6,124 Mg, 0,203 Zn, and balance Al.

The AD-1 alloy was a rolled sheet u of 2 mm thickness with chemical composition (mass fraction, %) of 0,301 Fe, – 0,28 Si, 0,0251 Mn, 0,149 Ti %, 0,0441 Cu, 0,0439 Mg, – 0,0762 Zn, and balance Al.

The Ma2-1 magnesium alloy used in the present investigation was a bar of 60 mm diameter with chemical composition (mass fraction, %) of 4.36 Al, 1.34 Zn, 0.39 Mn, 0.09 C, 0.05 Si, 0.02 Fe, 0.01 Cu, 0.01 Cr, 0.005 Ni and balance Mg. Magnesium alloy bar was cat into disk plates with a thickness of 2.0 mm and into blocks with a dimensions of 6 mm × 6 mm × 12 mm.

The VT5-1 alloy was a rolled sheet u of 1,5 mm thickness with chemical composition (mass fraction, %) %, 4,311 Al, 0,211 Fe, 0,0116 Si, 0,864 V, 0,2786 Zr, 2,110 Sn, and balance Ti.

The grain sizes of interior volumes of specimens of AMг6, AD-1, Ma2-1, BT5-1 were equal to 45, 100, 40, 20 μm correspondingly.

Blocks from AMg6 and Ma2-1 were used for tests of materials at an axial compression. Specimens for tension tests have been fabricated of disks and sheets of explored metal alloys.

Specimens have treated by the surface severe plastic deformation (SPD) method. We use surface mechanical attrition treatment (SMAT) of opposite surface of specimens and all surface of blocks by spherical tungsten striker. The SMAT process consists of repeated impacts of a high-energy striker on the specimen surface under a controlled frequency of 25 kHz. In a result of SMAT the ultrafine grained layers were created.

The structure near surface was studied in traversal section of specimens. The fragment of 3-4 mm has been cut mechanically from a working part of samples with a structured surface layers. The plane of cut has been oriented orthogonally to the specimen surface.

The surface of section of samples was ground, polished and etched.

Methods of research. The structure was studied with application of optical inverted microscope Olimpus GX and scanning probe microscope NTEGRA NT-MDT. The influence of strain rate and nano-structured surface layers on the mechanical behavior of aluminium and magnesium alloys were studied under quasi-static and dynamic tension and compression loads. Quasi-static tests were performed using an Instron universal testing machine, and VHS-Instron servo-hydraulic machine. The Instron drop weight testing machine and a Split Hopkinson Pressure Bar (SHPB) were used for compression dynamic tests. Ultra high speed camera FASTCAM SA5 model 775K-M1 was used for photo registration of deformation and crack propagation of specimen at dynamic loadings at record rate of 262500 fps.

Influence of structured surface layers on deformation and fracture of aluminium and magnesium alloys at high strain rates was investigated by computer simulation method. Multi-scale computational model was used for the investigation of deformation and fracture of samples with the structured surface layers under dynamic loadings.

Results and discussion.

Fig 1 shows the nanostructured surface layer on titanium alloy VT-5 after SMAT.

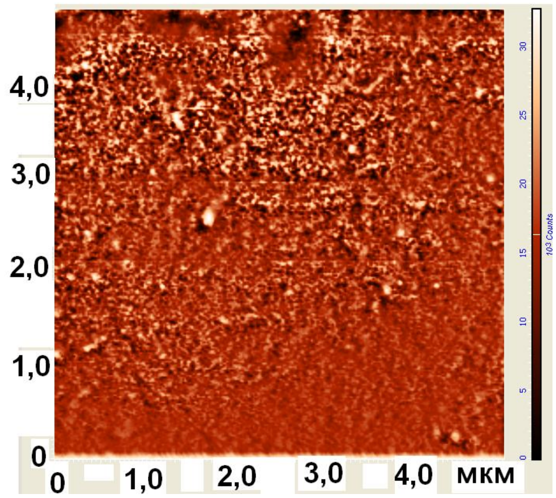


Fig.1. Nanostructured surface at titanium alloy VT-5.

Ultrafine-grained and nano structured layers were generated in all specimens. Interface boundaries in structured layers are fuzzy. Their thickness on different sites of a surface can vary on 20-25 %. The general thickness of the structured layer in the investigated alloys, as a rule, was equal to 30-40 microns.

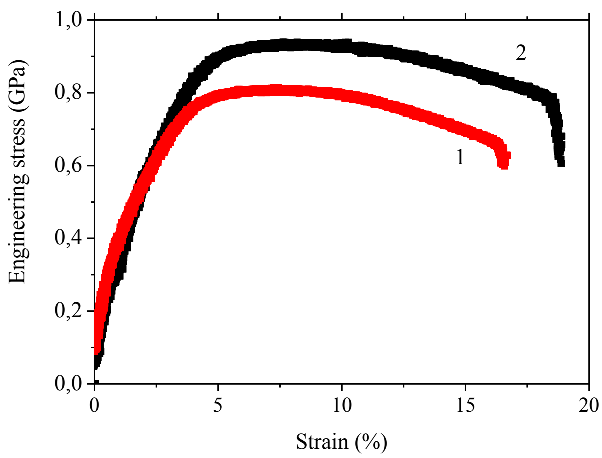


Fig.2. Tensile engineering stress-strain curves of VT5-1 titanium alloy at strain rate 10^{-3} s^{-1}.

Fig. 2 shows stress-strain curves under tension at temperature 295 K of VT5-1 alloy in a as-received condition (curve 1) and after SMAT (curve 2). The yield stress and elongation-before-fracture at quasistatic tension rise under formation of the structured layers on both sides of samples. Fig. 3 shows stress-strain curves under tension of AMg6 aluminum alloy at temperature 295 K. Curves 1 and 3 correspond to samples as-received condition and curves 2,4 and 6 obtained for samples after SMAT. Strain rates under tension were 8 10^{-3}, 8 10^{-3}, 485, and 552 s^{-1} for curves 1-4 correspondingly. Strain rates under compression were 480 and 550 s^{-1} for curves 5 and 6 correspondingly. Formation of the 20 μm structured layers on both sides of samples caused the increase of the yield stress and ductility at quasistatic tension. Specimens of AMg6 alloy after SMAT were fractured under exceeding of 18 % elongation strain at room temperature. The elongation before fracture was found to be enhanced on 20 - 25 % relative to the untreated alloy samples.

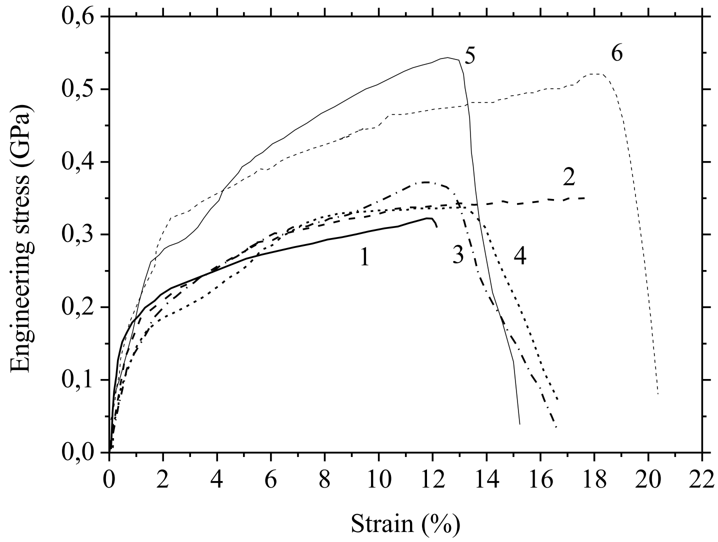


Fig.3. Tensile and compression engineering stress-strain curves of AMg6 aluminum alloy.

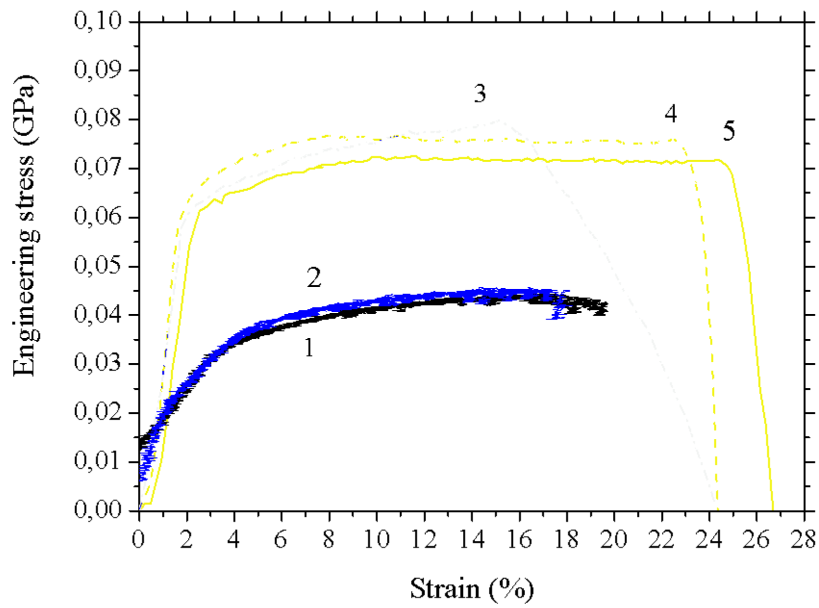


Fig.4. Tensile engineering stress-strain curves of AD-1 aluminum alloy.

Fig. 4 shows stress-strain curves under tension of AD-1 aluminum alloy at temperature 295 K. Curves 1 and 3 correspond to samples as-received condition and curves 2,4 and 5 obtained for samples after SMAT. Strain rates under tension were 8 10^{-3} (curves 1,2), 510, 504, and 501 s^{-1} for curves 2,3, and 4 correspondingly.

Elongation-to-failure after the SMAT increased at dynamic loadings both under tension and under compression. The yield stresses under compression are significantly higher flow stresses relative to tension. The yield stress and elongation-to-failure under tensile strain rate of 10^{-3} s^{-1} of Ma2-1 magnesium alloy after SMAT are increased as shown in Fig.5. At compression strain rate of 10^{-3} s^{-1} the yield stress increased too (curve 2 of Fig.6) but elongation-to-failure decreased.

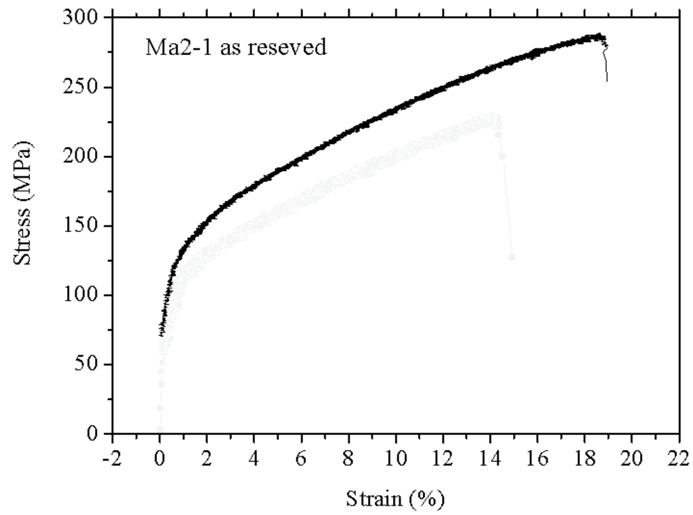


Fig.5. Tensile engineering stress-strain curves of Ma2-1 magnesium alloy.

Results of compression tests at strain range from 10^{-3} s^{-1} (curves 1 and 2), 228 s^{-1} (curves 3 and 4) and 3300 s^{-1} (curves 5 and 6) are shown in Fig.6. Curves 1, 3, and 5 correspond to compression of specimen of Ma2-1 alloy in as-received condition. The influence of structured surface layers on the mechanical behavior of magnesium alloy becomes insignificant at strain rates exceeding 100 s^{-1}. The reason of this effect has been found out at the analysis of high-speed registration of deformation of the samples.

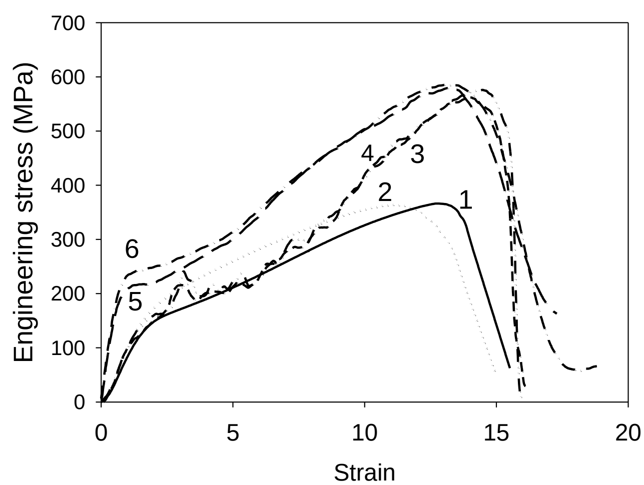
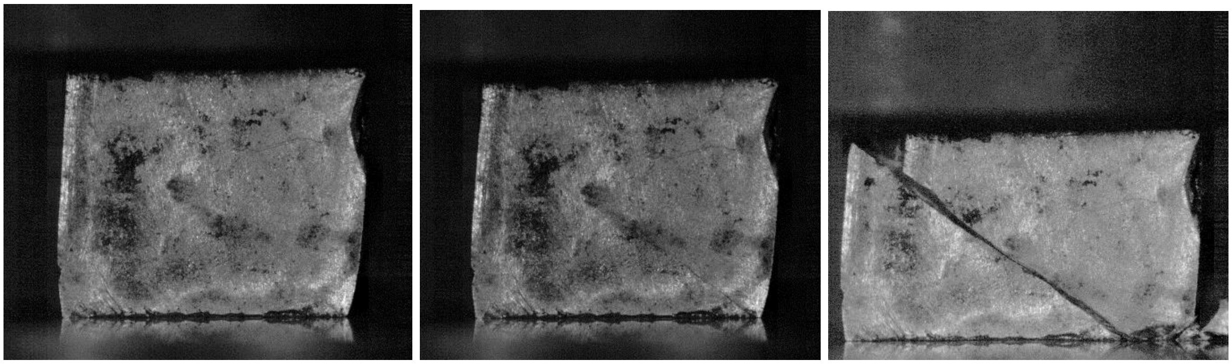


Fig.6. Compression engineering stress-strain curves of Ma2-1 magnesium alloy.

Fig. 7 shows that failure of specimen under compression at strain rates exceeds 100 s^{-1} are caused by the nucleation of the mesoscale shear band and its transformation into a shear crack. Strain rate is equal to 228 s^{-1}. Structured surface layers and caused local stresses don't influence on localization of plastic flow in internal volume of bulk sample. But structured surface layers affect on the homogeneity of specimen's deformation and a neck formation under tension.

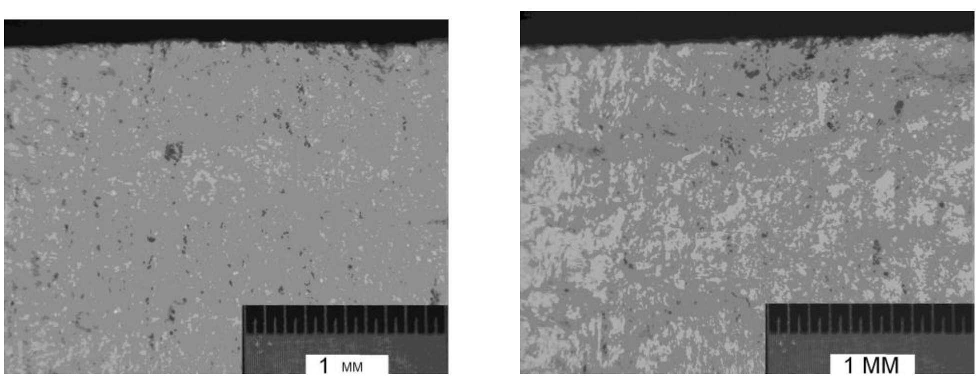


a **b** **c**

Fig. 7. Frames of high speed recoding of fracture nucleation in specimen of Ma2-1 alloy after SMAT.

Failure of the alloys occurs by shear failure under approximately 45° of inclination. Similar failure behavior was observed under dynamic loading. Shear bands and shear crack nucleation and growth lead to decreasing of stress. These results are direct confirmation that the decreasing path of stress-strain curves before macroscopic fracture is associated with mesoscopic localization of plastic deformation, instead of with dynamical recrystallization process or structural transformation in dislocation sub-microstructure.

Relief of fractured surface contains the information about correlation between mechanisms of failure and structure evolution during plastic flow. Relief of fracture surfaces was investigated by the method of optical stereo-microscopy for studying of failure mechanisms of samples with structured surface layers. Fig. 8 shows fracture surfaces of Ma2-1 alloy specimen in as-received condition (a) and specimen after SMAT (b). Strain rate is equal to 694 s^{-1}.



a b

Fig. 8. Photos of fracture surfaces of Ma2-1 alloy specimens of with the structured surface layers under tension.

The Hausdorff fractal dimension of facture surfaces was determined by the triangulation method [10]. In this method the grid with the cell size of one unit of measure l is located on a relief of fractured surface. It defines positions of tops of a set of triangles. The areas of all triangles are summarized to receive the approached area of surface S (l). The size of a grid then decreases consistently twice on each step until l does not become equal to distance between two next points. The inclination of S (l) versus log (1/l) line corresponds to the Hausdorff fractal dimension $D_f - 2$. The Hausdorff fractal dimension D_f is used for quantitative description of fractals which describes invariance of statistical characteristics fracture surface at a various scale levels. Spectrum of fractal dimensions is used for a complete description of multifractal. Using of a multifractal approach allows allocating the enclosed fragments in studied object, for each of which the properties of self-similarity are observed. The analysis of dependences of the correlation sums from distance between points testifies to existence of three regions. These regions are displayed in fig. 9 as ΔL_1, ΔL_2, and ΔL_3. Fractal dimensions and top borders of correlation length corresponding to them can be defined for these regions.

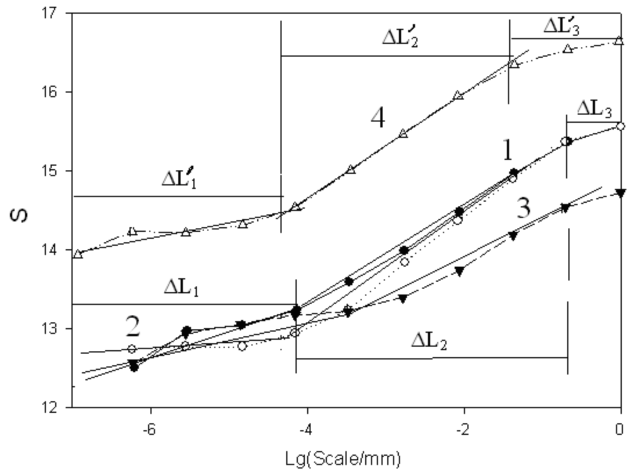


Fig.9. Fractal clusters on the fracture surface of aluminum alloy AMg6.

Fig. 9 shows the dependence of the correlation sum of S versus a distance between points of images of fracture surfaces of AMg6 aluminium alloy without SMAT (lines 1 and 2) and after SMAT (lines 3 and 4). Lines1 and 3 conform to quasistatic loading and lines 2 and 4 conform to dynamic loading. Fractal dimensions of a fracture surface of AMg6 alloy without SMAT is equal to D_f = 2,51 at quasistatic loading (region of L_2). Fractal dimensions for samples after SMAT are higher at quasistatic loading (D_f =2,52).

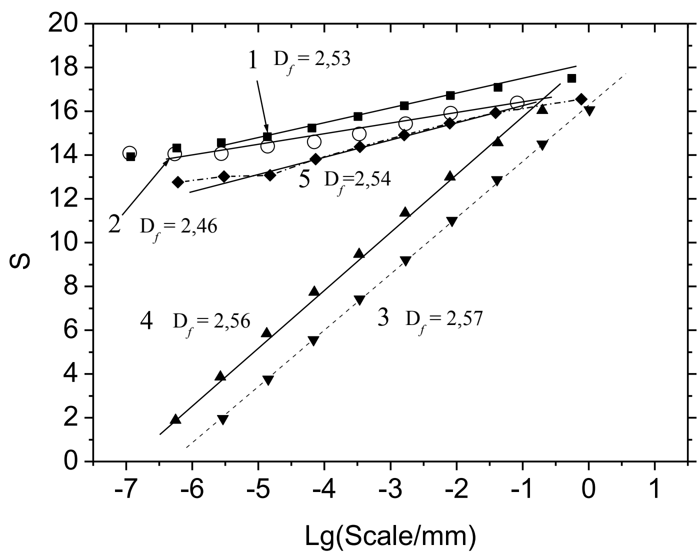


Fig.10. Fractal clusters on the fracture surface of Ma2-1 magnesium alloy.

The received results testify that the formation of structured surface layers causes changes of laws of destruction of samples of aluminum alloys. Increasing of fractal dimensions with growth of strain rate testify the self-organizing of microscopic and meso-scopic mechanisms of failure under dynamic loading. Self-organization of plastic deformation and fracture processes at lower structural levels under dynamic loadings of AMg6 alloy after SMAT is confirmed by existence several regions Δ_{L1}, $\Delta_{L'1}$, Δ_{L3} , and $\Delta_{L\ 3}$ without stable correlation between S (l) and log (1/l).

Fig. 10 shows fractal dimensions of a fracture surfaces of Ma2-1 alloy without SMAT (curves 1,2, and 5) and after SMAT (curves 3,4). Fractal dimensions D_f =2,53 (curve 1) and D_f =2,56 (curve 4) correspond to quasistatic tension. Fractal dimensions D_f =2,46 (curve 5) was determined for fracture surface of alloy without SMAT under quasistatic compression. Specimens with structured surface layers fractured under high rate tension have relief of fracture surface with fractal dimensions of D_f =2,57. In all investigated materials the formation of structured surface layers leads to increase of fractal dimension of a fracture surface under similar conditions of deformation. The received results testify that formation of the thin superficial structured layers leads to reduction of influence structural inhomogeneities near surface of specimens on the yield stress, the tensile strength and elongation-before-fracture under tension of materials, both at quasistatic and dynamic loadings.

Failure of specimen of light alloys under compression at strain rates exceeding of 100 s^{-1} and less than 1000 s^{-1} are caused by the nucleation of the mesoscale shear bands and their transformation into a shear crack.

Summary

The mechanical behavior of aluminium, magnesium and titanium alloys in as-received condition and after SMAT was investigated experimentally under quasi-static and dynamic loadings.

It is revealed a self-organization of mesoscale plastic deformation modes and shear localization, under quasi-static and dynamic loadings depends on structure of surface layers.

Self-organization of plastic deformation and fracture processes at lower structural levels take place under dynamic loadings of alloys after SMAT. These processes lead to change of localization deformation laws on mesoscale level with increasing of strain rate, and to decrease of the strain before fracture.

Failure of specimen of light alloys under compression at strain rates above 100 s^{-1} and less than 1000 s^{-1} are caused by the nucleation of the mesoscale shear bands and its transformation into a shear crack.

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