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SIMULATION OF REVERSED TORSION OF THE ALMG6 ALUMINIUM BAR USING THE MACRO-MOLECULE APPROACH

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Summary. *The specified macro-molecule approach is tested using the reversed-torsion load case for the 30×10×10 (mm) bar made of AlMg6 aluminium alloy. The work has two parts: the experiment part and the calculation part. The experiment is carried out using both the automatic INSTRON torsion machine and the AVERY torsion machine with manual control. The available backlash between the deformed bar and the torsion grip is taken into account. The calculation model is developed using the MSC.Adams software.*

The reversed-torsion load case consists of the nine modes: 1) original backlash mode (optional), 2) one-directional 90° torsion, 3) unloading, 4) backlash mode, 5) 60° torsion in the opposite direction, 6) unloading, 7) backlash mode, 8) 30° torsion in the original direction, 9) unloading. The AlMg6 macro-molecule force characteristic is selected under condition that the experiment torsion curve and the calculated torsion curve are as close as possible.

Continuity hypothesis is the main assumption of solid mechanics. This hypothesis is the main obstacle of its future development. The particle-based methods are free from this assumption, that is why they have a great potential. So, F. Spreng, A. Mueller and P. Eberhard [1] showed the possibility of analyzing the steel chip-formation process during machining operations using the bi-adaptive smoothed particle approach.

The considered macro-molecule approach is introduced in [2], where it is tested for the problem of compression of the duralumin bar. One-directional torsion of the fluoroplastic bar is tested in the work [3]. This issue specifies the approach testing results for the more complicated problem of reversed torsion of the bar made of the AlMg6 aluminium alloy. It is clear that the harder the material, the more difficult to integrate it. For example, the steel

problems are more difficult than the fluoroplastic ones. So, loading an aluminium alloy is the problem of moderate intermediate difficulty. The considered aluminium test specimen subjected to reversed torsion is shown in Figure 1. The specimen has a slight pink tinge because it has been photoed using the macro mode in the flash light.

This work consists of the two parts: the experiment part and the calculation part. The main feature of the considered reversed-torsion load case – is the backlash, that usually takes place between the test specimen and the torsion grip of the laboratory torsion machine. It imposes additional test conditions both on the experiment procedure and on the calculation model. The considered reversed-torsion load case consists of the nine modes: 1) original backlash mode (optional), 2) one-directional 90º torsion, 3) unloading, 4) backlash mode, 5) 60º torsion in the

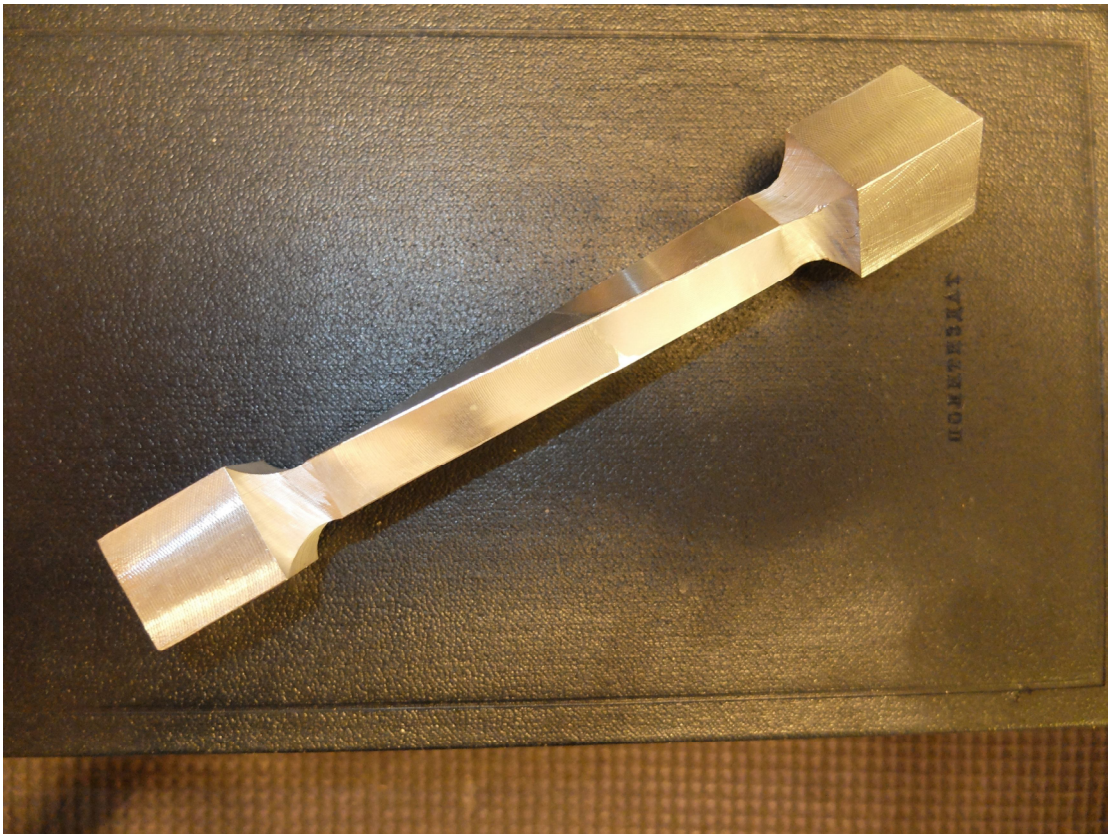

Figure 1: The deformed test specimen subjected to reversed torsion

opposite direction, 6) unloading, 7) backlash mode, 8) 30º torsion in the original direction, 9) unloading. Backlashes introduce essential uncertainty. That is why not all the automatic laboratory torsion machines provide the required reversed-torsion load case. In this work, the available INSTRON automatic machine provides only the second mode of the load case: one-directional 90º torsion. The main experimental results are obtained using the AVERY torsion machine with manual control. Figure 2 specifies fixing the test specimen with a backlash in the torsion grip of the AVERY torsion machine. Each time during the backlash test mode, the

Figure 2: Fixing the test specimen with a backlash in the torsion grip of the AVERY torsion machine

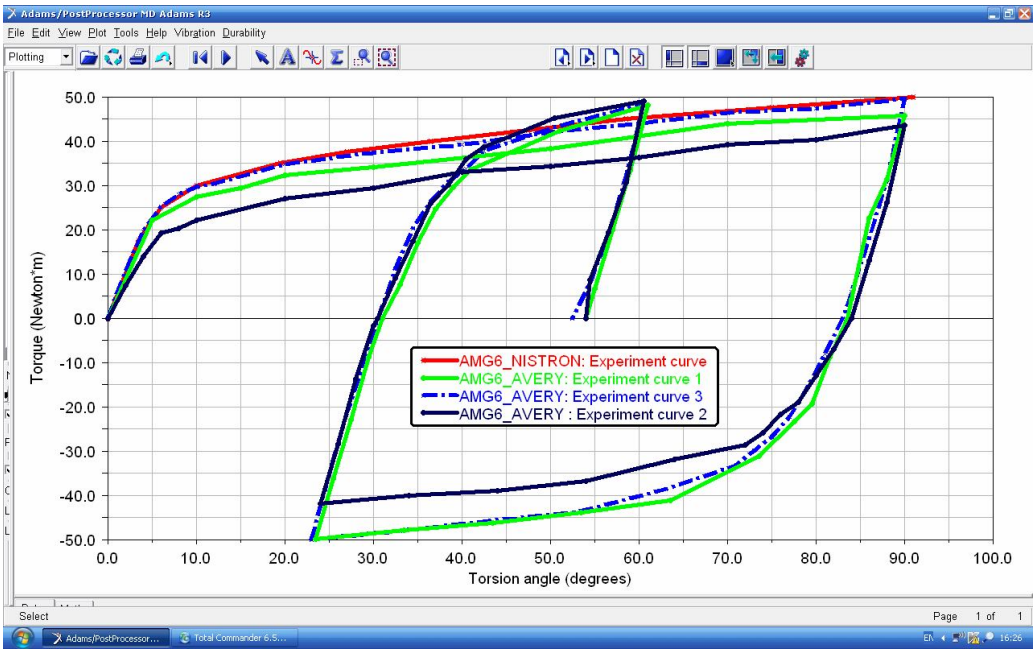

Figure 3: Obtained experiment results:
- red segment of the one-directional 90º torsion mode (INSTRON machine);
- three different-color interpolated hysteresis curves of reversed torsion (AVERY machine, see also corresponding black discontinuous curves in Figure 11).

laboratory master takes the specimen out of the grip and adjusts the machine. It is also impossible to catch the zero point at the end of the unloading mode. The representative set consists of four specimens: the one tested using the automatic INSTRON machine and the three tested using the AVERY machine with manual control. The obtained experiment torsion curves are presented in Figure 3. Corresponding representative set of resultant interpolated curves have traditional hysteresis character. They have this essential random scatter. Corresponding non-interpolated reduced discontinuous torsion curves are presented hereafter in Figure 11 in comparison with the obtained calculation curves. The driven-grip rotation speed is approximately from 10 to 20 degree/second. The aim of this work is to show that the AlMg6 aluminium macro-molecule force characteristic may be selected properly under condition that the experiment reversed-torsion curve and the calculation reversed-torsion curve are as close as possible.

The considered calculation model is presented in Figure 4. It represents only the central 1/3 part of the test specimen (see Figure 1). So, the (+90º, −60º, +30º) reversed-torsion load case is reduced to the (+30º, −20º, +10º) one. This 30×10×10 (mm) part is made of 10×4×4=160 macro-molecules arranged in the nodes of the cubic design lattice. Other model approximations containing 7×3×3=63 macro-molecules and 4×2×2=16 macro-molecules are also considered to analyze convergence of the considered calculation procedure. Different

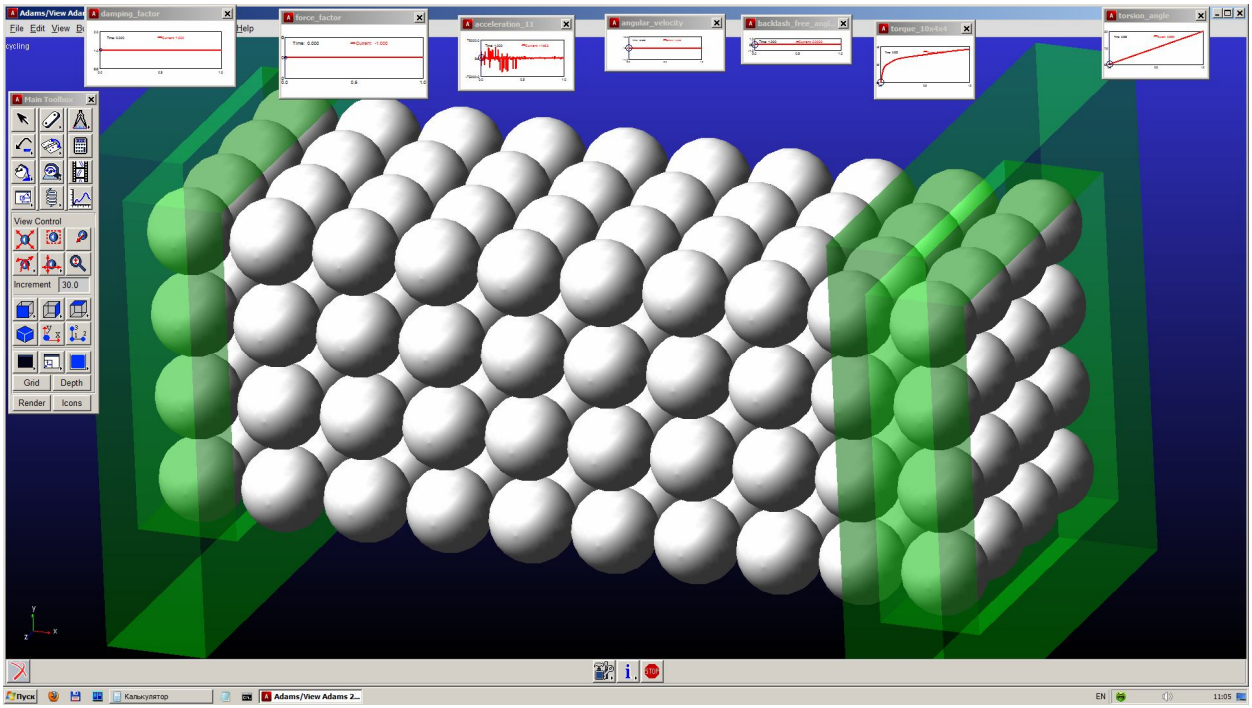

Figure 4: The AlMg6 aluminium bar model made of 10×4×4=160 macro-molecules using the MSC.Adams software

lattice approximations are specified by their different lattice distance *l*. Total mass of the model is distributed uniformly between the particles. Figure 5 specifies interaction of macro-molecules using the MSC.Adams interface. The red lines indicate interaction between the macro-molecules (each one with each one). The white lines (intersecting in the same corner of the torsion grip) indicate interaction of the outermost edged macro-molecules with the torsion

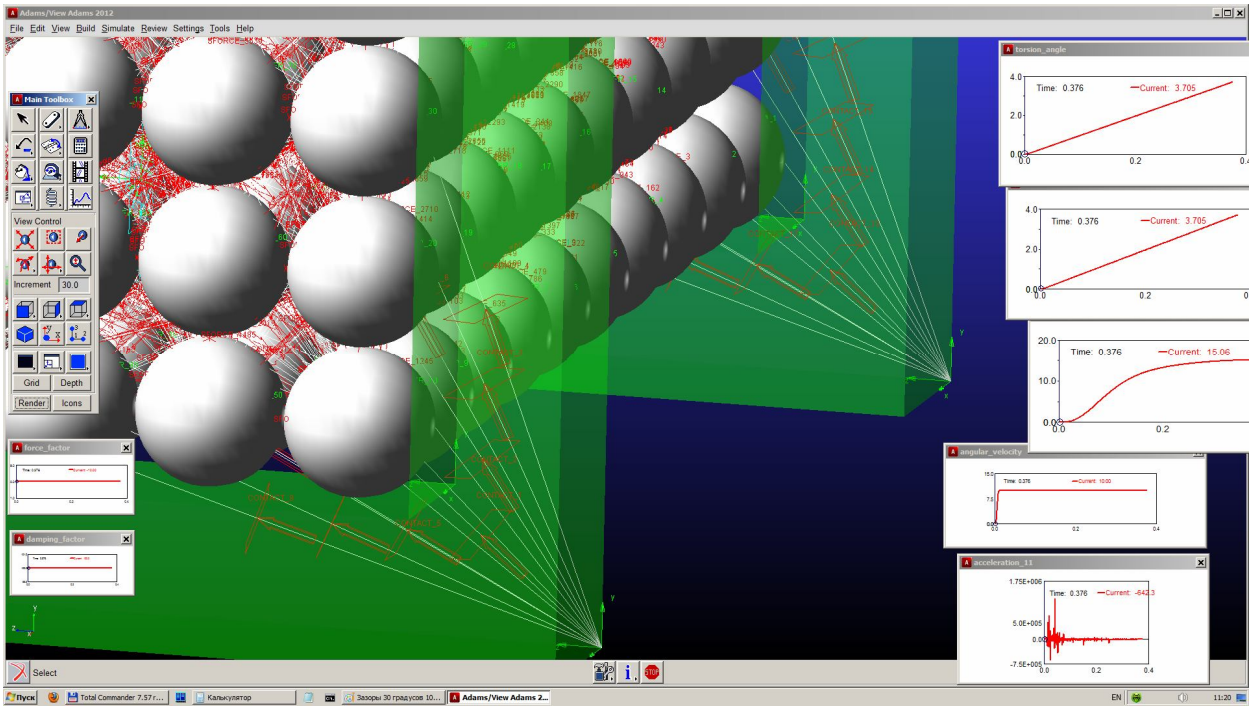

Figure 5: Interaction of macro-molecules between each other and with the torsion grip presented using the classic MSC.Adams interface

grip. The number of the specified interactions is high, and it is impossible to impose them all by just picking the screen of the computer. That is why a special computer program has been developed using the internal View Command Language of the MSC.Adams software. The torsion grips are transparent green in order not to hide the background. The left grip is connected to the ground using the elastic-damping torsion element. Its damping component is extremely high. So the grip is considered to be fixed and motionless. The torque determined in this connection element is taken as the resultant torque of the calculation torsion curve (see Figure 11 hereafter). The right grip is driven in compliance with the reduced load case requirements. There is the backlash between the deformed test specimen and the torsion grip (see Figure 6). During the backlash mode, the torque is equal to zero.

Interaction between the macro-molecules is provided by their force field. The force field is determined by the macro-molecule force characteristic. Interaction of macro-molecules and the torsion grip is provided by the contact of the sphere surface of the particle (see Figure 5) and the flat internal surface of the grip. This contact is calculated using the standard internal

function CONTACT of the MSC.Adams software. The contact force has two components: the normal component depending on the mutual penetration depth and the tangential Coulomb-friction component (steel/aluminium friction factor is taken equal to 0.61). Both the normal contact-force component and the tangential contact-force component are specified using the

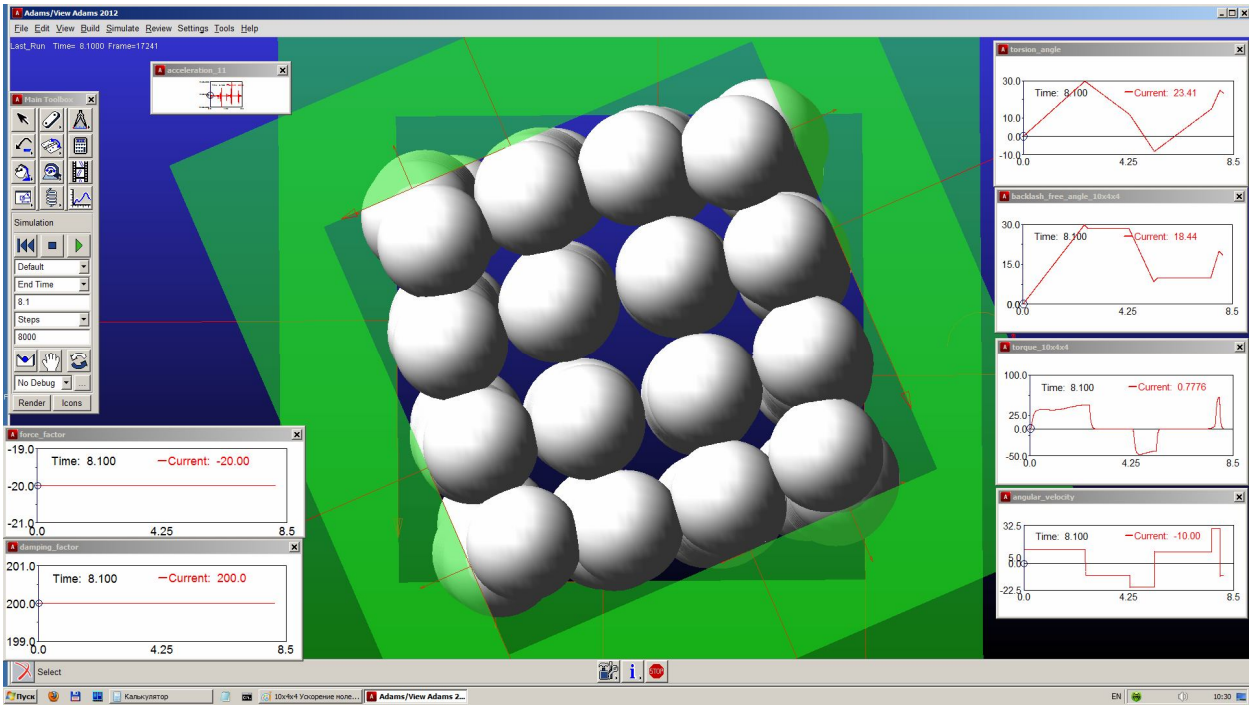

Figure 6: The backlash (contact-free zone) is available between the deformed test specimen and the torsion grip

scaled arrowed lines in Figure 6. The considered macro-molecules are subjected to translational motion only. Their rotation velocity vector is taken equal to zero.

It is important, that the widely used unimodal and monotonous force characteristics of Lennard-Jones type does not fit here (it may be considered only as the envelope). The fact is that it can not in principle provide the required equilibrium state of the micro-molecules arranged in their initial positions in the nodes of the design lattice. The force characteristic shall be equal to zero in the lattice nodes. That is why the force characteristic shall have several roots and this oscillation character.

The required number of roots of the considered force characteristic depends on the value of the assumed interaction range and, consequently, on the considered number of the macro-molecule essential neighbors. All the neighbors of the considered macro-molecule may be divided into several groups by their distance. This distance is the same within a separate group. Any one representative particle of the group is the essential neighbor. The shortest interaction range is equal to $2l$ (see Figure 7), and corresponding possible interaction distances are: l, $l\sqrt{2}$, $l\sqrt{3}$ and $2l$. So all the short-range neighbors may be divided into four groups, and there are only four short-range essential neighbors (see Figure 7).

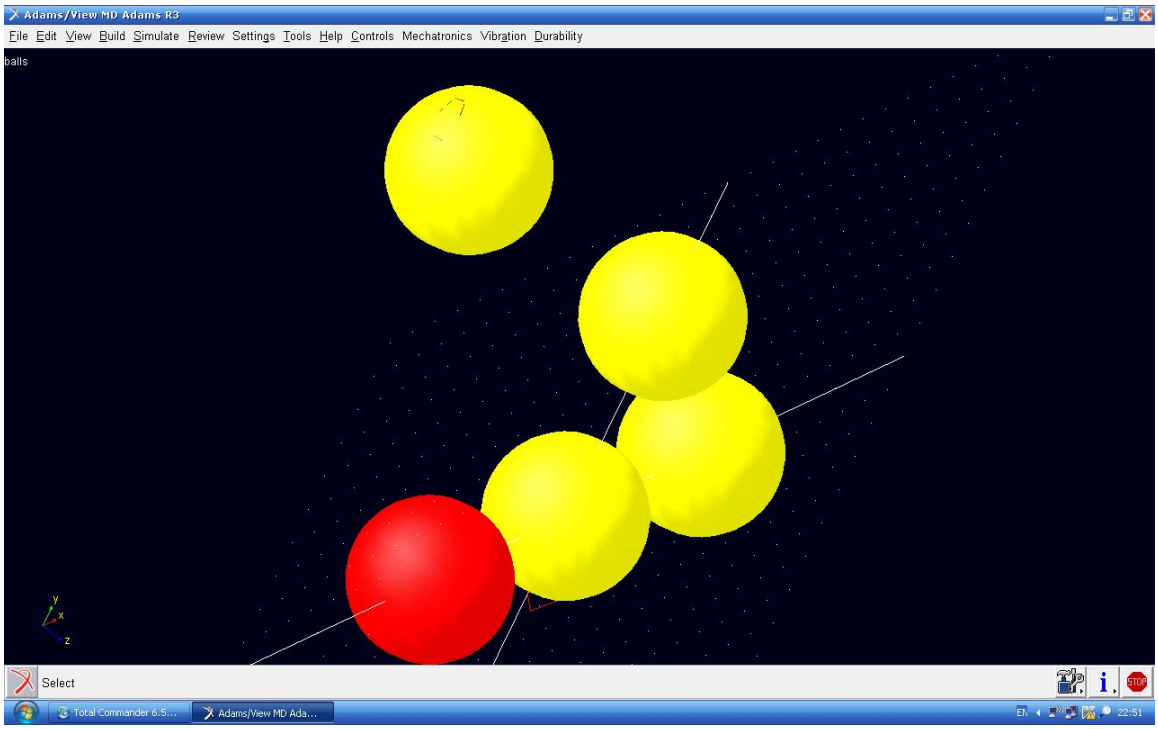

Figure 7: Four short-range essential neighbors of a macro-molecule (red one)

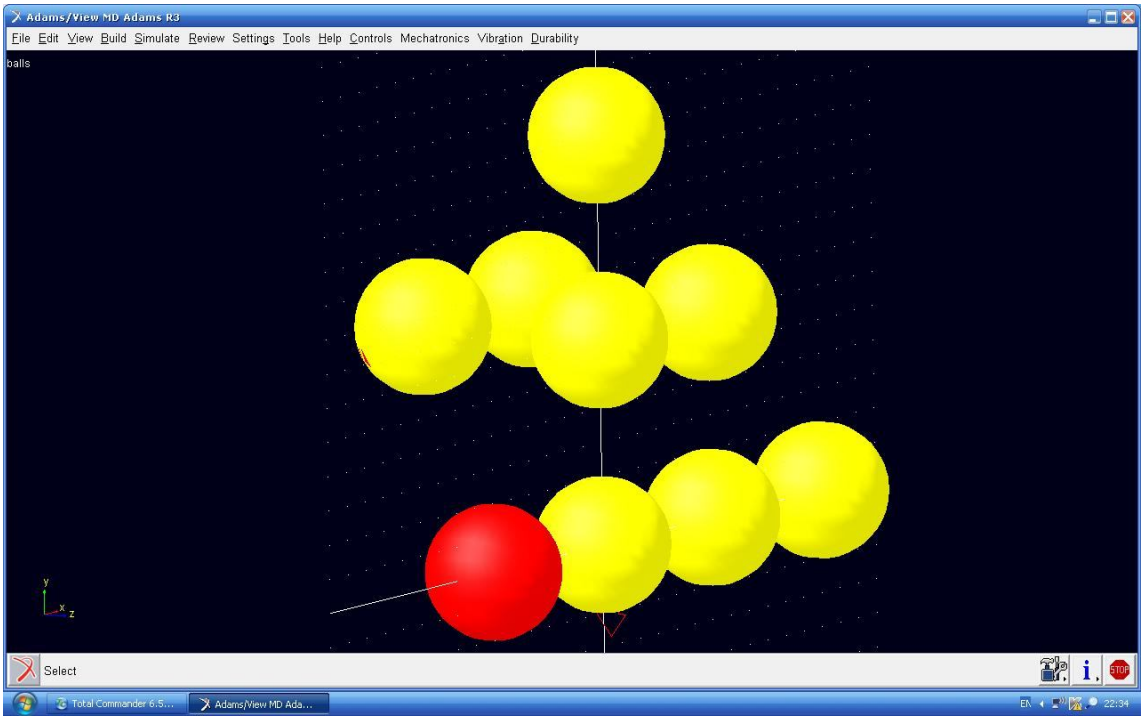

Figure 8: Eight medium-range essential neighbors of a macro-molecule (red one)

If the interaction range is equal to $3l$ (medium interaction range, see Figure 8), then eight possible interaction distances are available: l, $l\sqrt{2}$, $l\sqrt{3}$, $2l$, $l\sqrt{5}$, $l\sqrt{6}$, $l\sqrt{8}$ and $3l$. So all the neighboring particles may be divided into eight groups, and only eight medium-range essential neighbors are available. This speculation may be continued.

In this work, the macro-molecule interaction is considered to be the short one, and the corresponding force characteristic has at least four roots. But that is not enough. The fact is that the equilibrium state shall be also stable in a lattice node, and the derivative of the curve shall be positive in all the four corresponding points. So three additional intermediate roots shall be taken into account. They are selected in the middle between each two adjacent roots:

$$a_1 = l; a_2 = \frac{l(\sqrt{2}+1)}{2}; a_3 = l\sqrt{2}; a_4 = \frac{l(\sqrt{2}+\sqrt{3})}{2}; a_5 = l\sqrt{3}; a_6 = \frac{l(\sqrt{3}+2)}{2}; a_7 = 2l \qquad (1)$$

Finally, we have the seven-root force characteristic for the short-range calculation scheme. The example is represented in Figure 9 for the 7×3×3=63 macro-molecule approximation of the 30×10×10 (mm) bar. Going this way, we have the 15-root force characteristic for the

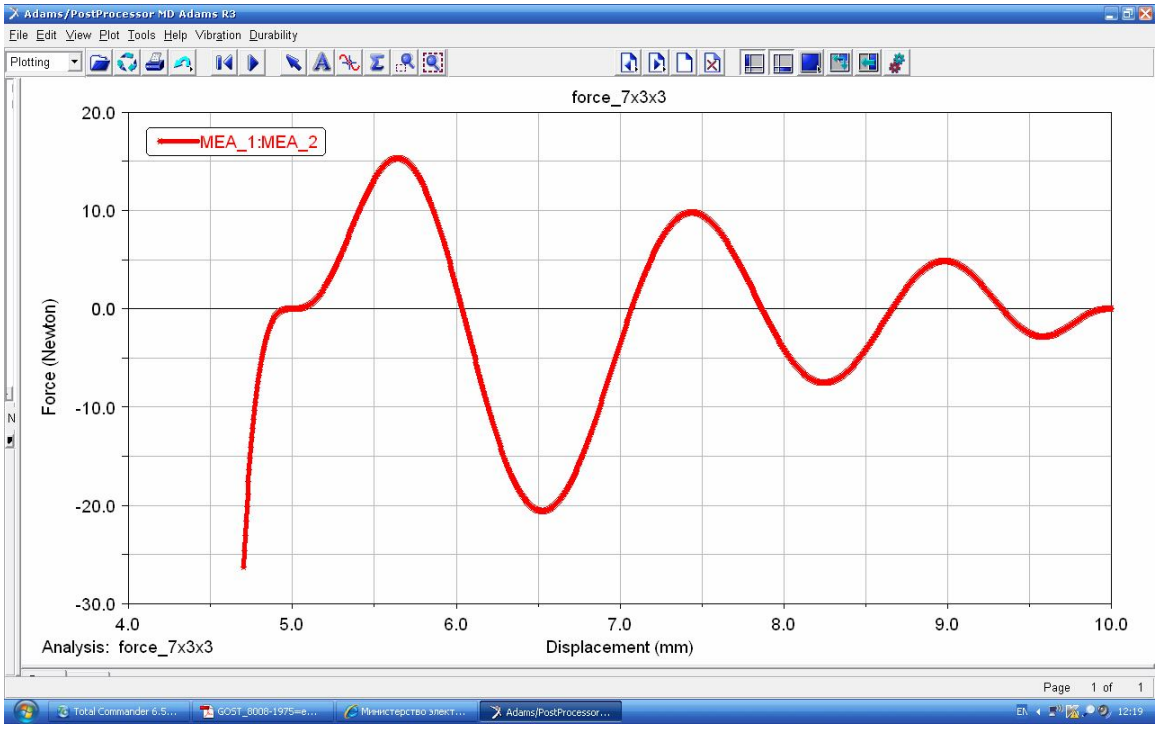

Figure 9: Seven-root force characteristic of the short-range macro-molecule calculation scheme

medium-range calculation scheme, etc. The considered AlMg6 aluminium alloy is an isotropic material, and its spacial macro-molecule force field shall comply with the requirement of central symmetry.

The calculations show that torsion is not a continuous and monotonous static process. Actually it is a sequence of step-like transitions of the considered macro-molecule system from the vicinity of one equilibrium state to the vicinity of another equilibrium state. During this torsion, some macro-molecule substructures are subjected to destruction, and new substructures take place. This transition process from one equilibrium state to another is an extremely dynamic one. It is studied using the torsion dynamic equations forming the Cauchy problem with initial data. Solving this problem requires a high-order integration procedure.

The torsion dynamic equations of the considered macro-molecule system are given by:

$$\begin{aligned} & -m_j \ddot{\vec{r}}_j - \sum_{\substack{k=1 \\ k \neq j}}^{n} \vec{F}_{jk} + \vec{F}_{jleft} + \vec{F}_{jright} = 0 \\ & j = 1...n \end{aligned} \tag{2}$$

where: n – number of macro-molecules; m_j – macro-molecule mass; $\vec{r}_j$ - macro-molecule radius-vector; $\vec{F}_{jleft}$ and $\vec{F}_{jright}$ - contact forces determined by the CONTACT standard procedure of the MSC.Adams software. Rotation of the macro-molecules is not available.

$$F_{jk}(x_{jk}) = A(x_{jk} - a_1)^p [\prod_{i=1}^{7} (x_{jk} - a_i)] step(x_{jk}, 2sl, 1, 2l, 0) + fx_{jk} \tag{3}$$

- is the macro-molecule force characteristic. It is the interaction force between the two macro-molecules arranged at a current distance x_{jk} from each other. a_i - are the roots of the force characteristic. The considered force characteristic has two components: the positional component (see Figure 9) and the damping component. The positional component is mainly the product of binomials. A – is the force factor, f – is the damping factor, p – is the envelope growth-rate factor. The calculations show that integration of the equations (2) is practically impossible unless damping is taken into account. The pair (A, f) – is the required characteristic of the AlMg6 aluminium alloy in the given interpretation.

It is assumed, that the particles start to interact when the distance between them is less than $2l$. This is the short-range interaction with four essential neighbors (see Figure 7). Its logics is determined by the function *step*(…) (3). It is a standard function of the internal language of the MSC.Adams software. This function is the cubic polynomial given by:

$$\begin{aligned} & y = ax^3 + bx^2 + cx + d \\ & x \in [2sl, 2l]; s \in (0.5, 1.0) \end{aligned} \tag{4}$$

$$B = -\frac{(s-1)^3}{2}; a = \frac{1}{Bl^3}; b = -\frac{3(1+s)}{2Bl^2}; c = \frac{3s}{Bl}; d = \frac{1-3s}{2B}$$

where: s – is the decrease-rate factor of the envelope of the positional component of the force characteristic within the [l, $2l$] interval (see Figure 9).

The equations (2) are solved using the high-order Hilber-Hughes-Taylor (HHT) integrator from the rest (initial equilibrium) state. Figure 10 specifies a regular oscillation process for acceleration of the particle arranged in the lower right-hand corner of the torsion grip (see Figure 6). All the considered nine modes of the reversed-torsion load case are available. The acceleration amplitude has its maximum values at the moments of the contact origination and at the moments of the contact loss. The oscillations are not available during the three backlash modes (with the original one in that account). The presented power spectrum density (PSD) function shows a wide spectrum of the considered oscillations.

The left motionless torsion grip (see Figure 4) is connected to the ground using a damping element. That is why the resultant calculation curves presented in Figure 11 are free of oscillations. The available backlash modes are omitted here. Three black curves – are the reduced non-interpolated experiment torsion curves (see also Figure 3 above). The three other different-color curves are the obtained calculation torsion curves. The pair (A, f) components are selected under condition that the experiment curves and the calculation curves are as close as possible. The available decrease character of the strengthening segments of the higher-approximation torsion curves may be explained by assuming the short-range interaction model. The 10×4×4=160 reversed-torsion load case requires approximately 7 hour operation of a regular computer containing 24 Gbyte RAM and 3 GHz processor.

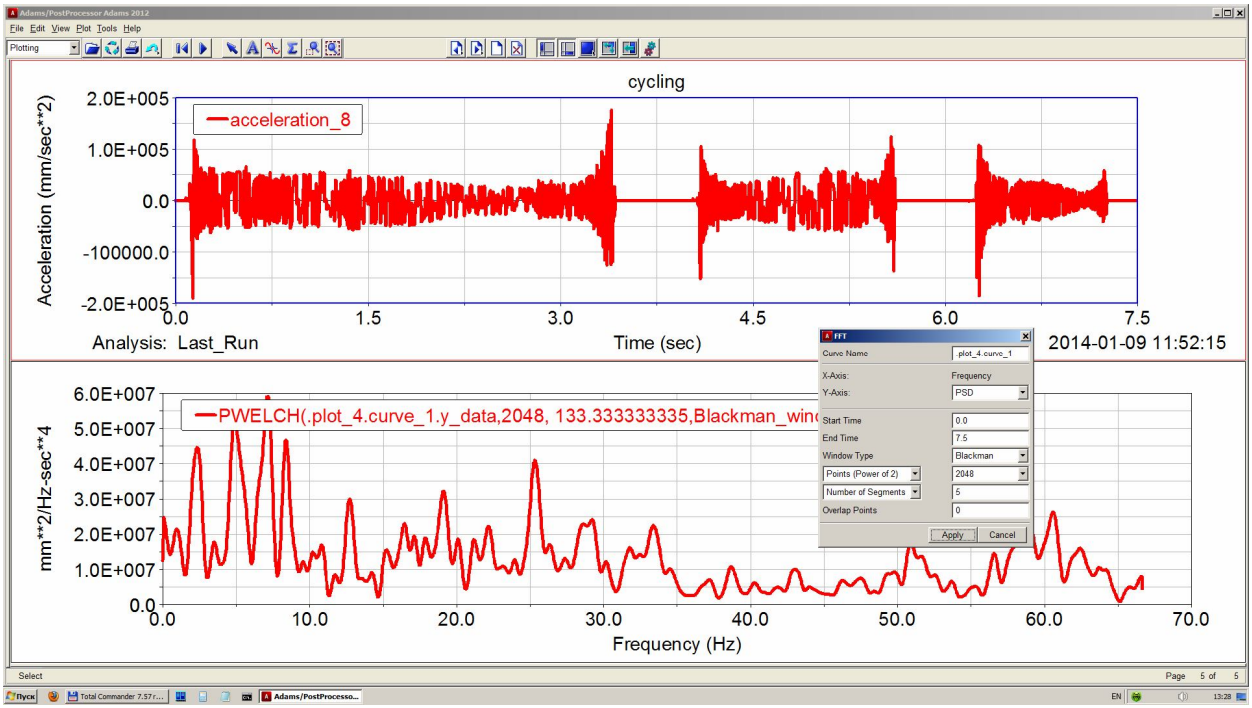

Figure 10: Wide-spectrum macro-molecule oscillations during the reversed-torsion process

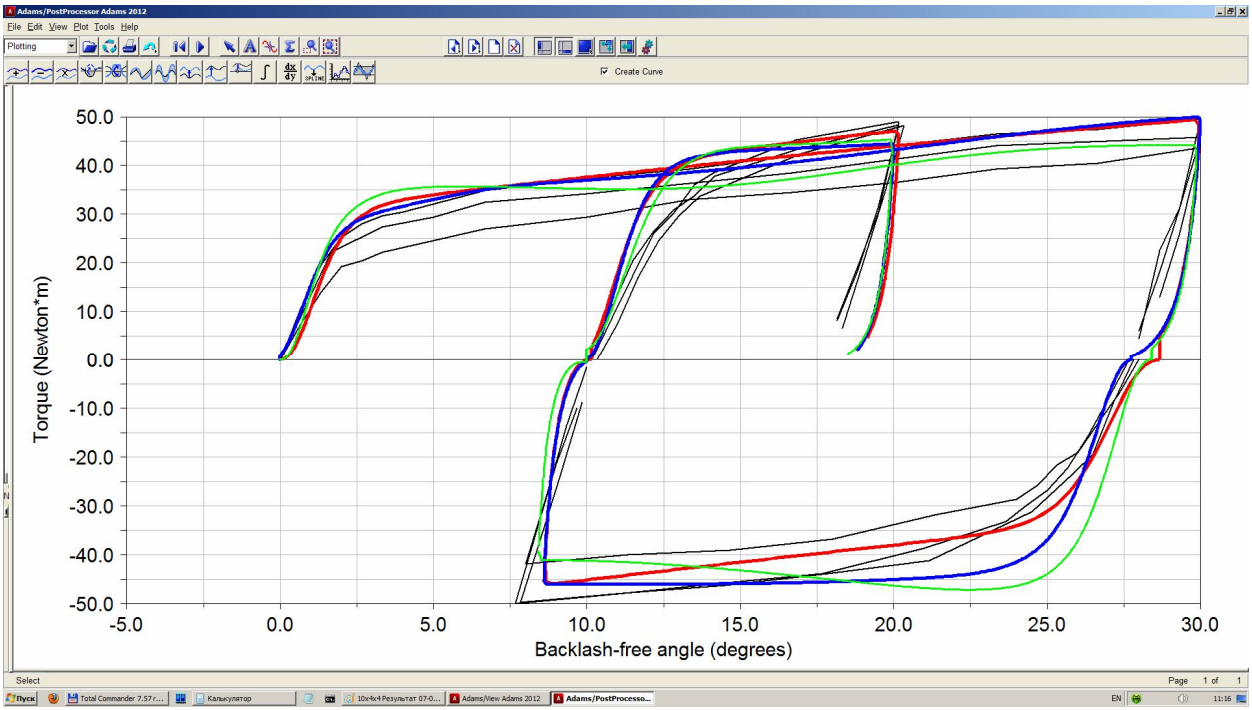

Figure 11: Convergence of calculation results:
- three black discontinuous experiment curves reduced to the (+30º, −20º, +10º) load case;
- red, blue and green calculation curves of the 16-molecule, 63-molecule and 160-molecule approximations correspondingly

CONCLUSION

- the submitted macro-molecule approach provides satisfactory results for solving the problem of intensive reversed torsion of the bar made of the AlMg6 aluminium alloy with the torsion-grip backlash taken into account.

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