

STUDY OF TWO-SHAFT SHREDDER FOR CRUSHING OF CONCRETE, RUBBER, PLASTIC AND WOOD

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Abstract

This work presents two-shaft shredder for concrete, rubber, plastic and wood crushing. The existing machine structures have been described, and classification has been made. Analysis of their advantages and drawbacks was performed. Conclusions about the selection criteria for the machines, as the main equipment for technogenic and construction waste recycling, have been made. The paper also presents calculation results and verification of the shredding shafts and chamber of a two-shaft shredder. Modeling analysis of the shredding shafts and chamber has been performed. The studies of the mechanical load and behavior of the shredding shafts and chamber have been conducted. For this purpose, there has been generated a three-dimensional geometrical model of the shafts and chambers, which digitized a planned network of finite elements in the programming environment of ANSYS MECHANICAL APDL.

Key words: two-shaft shredder, crushing, modeling analysis

1. INTRODUCTION

The plastics and rubber products manufacturing, as well as intensive construction, leads to major waste accumulation and environmental hazard. In all industrial societies are essential and necessary household and technogenic waste reducing and their reintegration into the manufacturing process.

The global industrial economy supports of industrial processes development, which in the highest level utilize material and energy resources. During the last decades the introduction of new, advanced and innovative technologies for reducing the raw materials and economic costs of enterprises are from essential importance for effective resource management. The industrial production requires raw materials that meet certain specific characteristics. Their finding into a natural environment gradually becomes an impossible task, and their yield leads to a release of significant waste quantities, water and energy high consumption.

That is the reason some of the industries to be directed not only to reduce the quantities, but also the waste products recycling and inclusion of already recycled materials in the technological process. In this way the solid waste generation is regulated and the fossil minerals consumption is essentially reduced.

The waste or recycled products use, which replaces the natural mineral forms for materials preparation, significantly alleviates environmental pollution. Adoption of measures to increase waste recycling and recovery is a priority for European and national waste management policy.

The waste management is a challenge, due to the high value of the numerous manual operations, high transport costs and negative impact on the environment. Therefore particularly important is study and development of the various machines for crushing of the diverse waste streams.

The recycling industry development shows increasing need of crushed materials with different composition and characteristics. New crushing machines creation, their research by adequate mechanical and mathematical models, engineering design and practical implementation are current scientific problem (Lowrison 1974).

The materials crushing for recycling purposes solves important environmental tasks related to environmental protection. They are dictated by the need for full and efficient use of most of the unprocessed waste products, which, on the one hand, are an important raw material for industry, and

on the other hand - lead to contamination if not utilized. These are serious preconditions for creating new technologies and machines for processing a wide range of secondary raw materials and waste.

The obsolete products from concrete, rubber, plastic and wood are processed by different methods, as determining is the final product and its intended use. Various complex solutions are known for reprocessing of the above mentioned types of waste and of the final product realization.

Disintegration as part of the recycling process can be successfully applied for domestic and industrial waste treatment, component and multi-component materials crushing, as well as for grinding of refuse utility with different mechanical characteristics – from the tough-elastic car tires and some types of plastics to the hard and brittle materials, such as glass, porcelain, chamotte, mica, concrete and others. (Abadjiev et al. 2007).

The crushing technological purpose depends on the following it next processes and stages of processing or the product application. Such an attitude towards the secondary materials is a prerequisite for sustainable development, as well as for the mandatory protection of people and environment (Vatskicheva et al. 2015).

Crushers are the main machines applied for crushing in the industry. Most of them are intended only for particular type processing. One alternative of the machines for secondary and waste materials crushing are the shredders. This is a group of relatively new machines which are classified mainly according to the number of the working shafts (Tonkov 2007), and the technology of crushing: single-shaft, two-shaft, three-shaft, four-shaft, five-shaft shredders, with varying automation degrees and key parameters control, noise different level, rotation speed, pressurization level and others (Abadjiev et al. 2007).

Shredders are configured according to each of their unique applications, with a selection of different thicknesses and number of cutting cogs, shaft diameter, thickness of the distance bushings, drive power, productive capacity. The knives are made through a specific technology from special steels. This ensures extreme hardness, duration of operation, and maintenance low cost.

The two-shaft hydraulic shredder consists of feeding conveyor, feed hopper, crushing chamber, output belt, unloading belt, and belt for metal particles separation. In the crushing chamber are arranged shafts which perform the main function of the machine. The two-shaft shredders advantage is their high productive capacity. The disadvantages are associated with the high price and the maintenance high cost.

In the present work is carried out a research of existing structures of multi-purpose shredders, the criteria for selection of shredder are specified, and is realized a model study of the chamber with the shredding shafts of two-shaft shredder for concrete waste crushing.

2. SUBJECT OF THE STUDY

Two-shaft shredder with its most loaded elements is the subject of the study. A serious advantage of the shredders is the possibility to be integrated into systems for simultaneous processing of different types of multi-component waste, with separation and utilization of the components having different degree of hardness.

One open engineering problem is the development of technology, in the bases of which are included machines of this type for old monitors recycling. As it is known, the monitors are made from plastic, glass and metal, and are necessary, without preliminary preparation, to extract from them all useful components. The components have to be obtained and separated in fine bulk, as in this form they should be delivered for subsequent stage-by-stage processing.

Similar problems also exist for old car tires recycling, waste cables, conductors and insulators, printed circuit boards, etc. Thousands tons of electrical and electronic equipment go out of use each year in Bulgaria. For the whole world these quantities are between 30 and 50 million tons per year. The wastes are generated by the industrial, commercial and household sector. They include electrical

supply equipment, power tools, household appliances, consumer electronics, phones and computer equipment, etc.

Based on previous research of multi-purpose shredders existing structures (Vatskicheva et al. 2013), it was found that could be developed a shredder, which may find application for wider range waste products recycling with improved energy efficiency compared to the mechanisms known until now.

2.1. Crushing machine selection criteria

The choice of crushing machine is determined by four main factors (Vatskicheva et al. 2013):

I factor: Material type for reduction.

For the crushing technique it is especially important to distinguish between destructions in macroscopic scale and those which result from the plastic deformation. Then distinguishing has to be made between brittle fractures and plastic breaking.

During the crushing process, we should by all means strive for the brittle fracture, since it is technologically more advantageous, and is realized with lower energy consumption. In most processes of mineral resources crushing a brittle fracture is present. Whether a brittle fracture during crushing will appear, or not, depends on the load conditions (temperature, loading speed, type of stress state, impact, pressure). For that we need to speak not for brittle materials, but for fragile behavior of the material.

There is a difference between materials that are prone to brittle fracture and those which are prone to plastic breaking. When increasing the load speed, the time is not enough for the necessary deformation movement, in order to obtain plastic deformation, from which follows that brittle deformation is favored (Mochev et al. 2013). This phenomenon also applies in case of the temperature lowering.

The selection of the shredder type is made according to the physical and mechanical properties of the crushed material and its strength characteristics. Shredders, working with impact and pressure, are used for brittle materials. Cutting single-, two- and four-shaft shredders are used for tough-plastic materials. The material may be crushed by scraping or cutting. For scraping are suitable single-shaft shredders (fig. 1a), which are crushing machines with universal application. They are intended for materials with great thickness and resistance against destruction. Their advantages compared to the other types shredders are solid and stable structure, long service life. A disadvantage is the low productive capacity, determined by the slow working speed. In crushing by cutting, selection can be made between single-shaft, two-shaft or four-shaft shredder (Vatskicheva et al. 2013).

The single-shaft shredders (fig. 1b) are rarely used for this type of materials crushing, because of their low productive capacity. Most often are used two-shaft shredders (fig. 1c). An advantage of the two-shaft ones is their high productive capacity. The disadvantages are the high price and the high cost of machines maintenance.

The two-shaft shredders realize the factual scissors effect, and the four-shaft ones provide larger zone of cutting (Tavakoli et al. 2008). The four-shaft shredders, shown on fig. 1d, are equipped with working shafts, on which there are installed cutting knives-disks. Both upper shafts are feeding, and the lower two – cutting. The existing two pairs of shafts (feeding and crushing) form a working chamber with conical shape (Borshev, 2004; FAG Spherical roller bearings E1, 2011).

Four-shaft shredders use has advantage in simultaneous reprocessing of different types large-dimensioned and elastic materials, as well as of materials, having free volume, for example various cans, containers, tanks, and others. Their disadvantages are related to the high price and the high cost of maintenance (Vatskicheva et al. 2013).

II factor: Size of the material for shredding.

The size of the crushed material determines the following characteristics of the shredder (Borshev 2004):

- Feed hopper dimensions and shape;
- Crushing chamber dimensions.



Fig. 1. Different types shredders

- (a) Single-shaft shredder, working by scraping; (b) Single-shaft shredder, working by cutting;
(c) Two-shaft and (d) Four-shaft shredders.

III factor: Productive capacity.

The shredder productive capacity (Q) shows the material quantity which is processed per unit of time. It is determined by represented formula (Borshev, 2004; Tavakoli et al. 2008):

$$Q = n \cdot b \cdot d \cdot z \cdot q, [\text{m}^3/\text{min}] \quad (1)$$

where: n – shaft revolutions of the crushing chamber, min^{-1} ;

b – shafts number;

d – number of disks on one shaft;

z – number of cogs on one disk;

q – material volume, torn off by one cog, m^3 .

IV factor: Final product particle-size distribution.

The particles size is a decisive factor in many industries. The influence of the final product on the selection of shredder lies in the following: as much as the size of the final product is smaller than the size of the source material, the time and effort should be spent for crushing increase. For particularly small fractions may be necessary second shredder, and sometimes whole production line, for example line for crushing to fine rubber powder. The output granulometry depends on the distance between the crushing disks (Abadjiev et al. 2007; Borshev 2004).

The specification of these four factors determines the best way for shredder design, manufacture and application. As an illustration of the above-mentioned four criteria is examined an example of shredder selection for concrete railway sleepers crushing, with the following output data:

- Material type – with high hardness, but also with great brittleness: concrete;
- Permissible pressure stress of the destroyed elements: $\sigma_{\text{pressure stress}} = 55 \text{ MPa}$ (Borshev, 2000);
- Railway sleepers overall dimensions: 2600 x 200 x 250 mm;
- Productive capacity – 10 t/h;
- Granulometry: (0 – 50) mm.

According to Factor 1: since the material is brittle, there will be used shredders, working on impact and pressure. *According to Factor 2:* the feed hopper and the crushing chamber are with overall dimensions corresponding to the railway sleepers overall dimensions. *According to Factors 3 and 4:* from the predetermined productive capacity by formula (1) is calculated the shaft revolutions (Borshev, 2004, Tavakoli et al. 2008):

$$n_V = \frac{Q}{b \cdot d \cdot z \cdot q}, [\text{min}^{-1}] \quad (2)$$

Constructively we accept:

- number of disks on one shaft: $d = 16$;
- number of cogs on one disk: $z = 3$;
- material volume, torn off by one cog: $q = 69,4 \cdot 10^{-3} \text{ m}^3$.

For single-shaft shredders ($b = 1$):

$$n_V = \frac{10\,000}{60 \cdot 1 \cdot 16 \cdot 3 \cdot 69,4 \cdot 10^{-3}} = 50 \text{ min}^{-1}.$$

For two-shaft shredders ($b = 2$):

$$n_V = \frac{10\,000}{60 \cdot 2 \cdot 16 \cdot 3 \cdot 69,4 \cdot 10^{-3}} = 25 \text{ min}^{-1}.$$

For four-shaft shredders ($b = 4$):

$$n_V = \frac{10\,000}{60 \cdot 4 \cdot 16 \cdot 3 \cdot 69,4 \cdot 10^{-3}} = 12,5 \text{ min}^{-1}.$$

After calculating the shafts revolutions have been calculated the rotation moment (M_V) in order to find the required shafts drive power (FAG Spherical roller bearings E1, 2011):

$$M_V = \sigma_H \cdot S_t \cdot \frac{D_t}{2} \cdot a, \text{ [N.m]}, \quad (3)$$

where: $\sigma_{\text{pressure stress}}$ - permissible pressure stress of the destroyed elements = 55 MPa;

S_t - the maximum contact area of each destructive cog $\sim 20 \times 30$ mm or $6 \cdot 10^{-4} \text{ m}^2$;

D_t - cutting disks diameter 300 mm (distance of the cogs from the shaft axis);

a - number of simultaneously working cogs. Based on the structure of the destructive disks drives is received that $a = 4$.

We replace the values in formula (3) and obtain:

$$M_V = 19\,800 \text{ N.m}$$

The required power P_V for propelling of each shredding shafts is determined on the basis of the formula (FAG Spherical roller bearings E1, 2011):

$$P_V = \frac{M_V \cdot n_V}{9554} \cdot \mu, \text{ [kW]}, \quad (4)$$

where: μ is safety factor: $\mu = (1,5 - 2)$.

When choosing $\mu = 2$, the following results are obtained:

- for single-shaft shredder: $P_V = 207,2$ kW;
- for two-shaft shredder: $P_V = 103,6$ kW;
- for four-shaft shredder: $P_V = 49,5$ kW.

When crushing various waste materials, the mechanical load of the machine elements is different. This can be best assessed through model studies. Additionally, a study of the designed machine most loaded details of conducted. These are the crushing chamber and shafts. The crushing chamber consist feed hopper and shredding shafts.

The feed hopper is constructed from hot-rolled sheet steel with additional ribbing. The hopper depth is 1000 mm, and the width in its upper part – 2400 mm. The hopper volume is $3,0 \text{ m}^3$. These dimensions are in conformity with the sizes of the crushed waste and the possibility for their wedging when they are placed in the hopper.

The chamber structure is verified for total strength, as applied are the loads from the shafts weight, the chamber elements, the feed hopper, as well as the support reactions in the bearings of the shafts. The studies were conducted through the mathematical models and procedures described below.

In the process operation, the shredding shafts are loaded with different forces and moments. From this perspective, the loads are divided into:

- Working loads: occurring during process operation;
- Permanent loads: do not change in size and direction;
- Variable loads: their variation depends on load systematic change, depending on the working cycles and random changes of the load due to various resistances types.

The shredding shafts, which are a subject of the study, are parallel, with length 900 mm, wheel-base 350 mm, and hexagonal cross-section. Crushing disks are mounted on the shafts. Between the discs to the housing of the camera, are mounted counter knives for cleaning the space between discs (fig. 2).

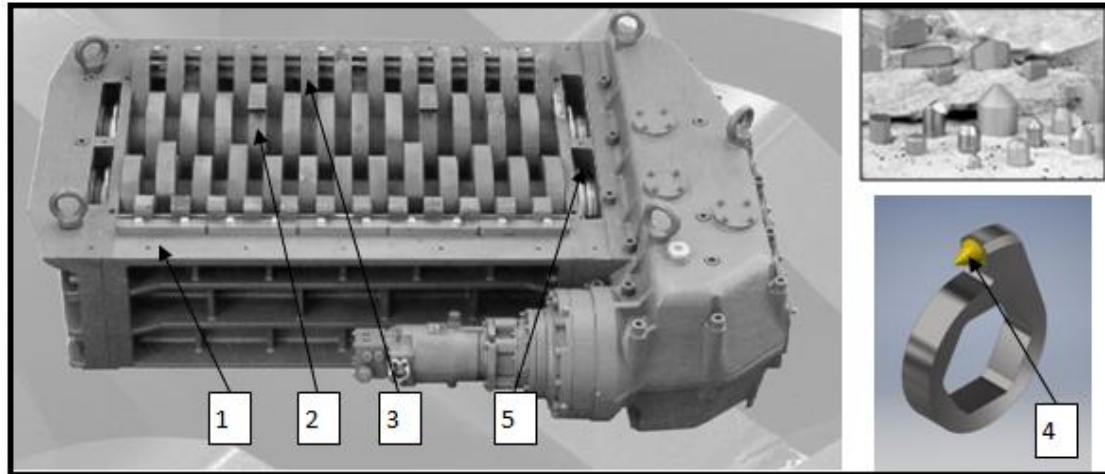


Fig. 2. Shredding shafts

- (1) Housing; (2) Crushing disks; (3) Counter-knives; (4) Removable cone;
(5) Apertures between the reducer and crushing chamber.

Crushing disks are double-topped. On each top is mounted a removable cone (4) from tungsten carbide with hardness HRC 60 - 64. The pressure exerted by the cone on the concrete should exceed the compressive concrete strength which is 55 MPa. The excess or shortage for crushing power is regulated through changes of the number of simultaneously operating disks and the number of the tops of each disk.

In case of drive re-dimensioning, it is possible to increase the destructive tops from two to three, whereat the productive capacity will increase with about 50%. Both crushing shafts are mounted in a common housing (1) through radial axial and radial roller bearings. The protection of the bearing units is three-stage.

The first is through apertures (5) between the reducer and the crushing chamber. The powder and the particles, having penetrated on the side of the shafts, fall through the apertures. The second stage is through double elastic sealants of the shafts axis. The third stage is through the bearings lubrication with oil under low pressure (3-5 bar), counteracting the penetration of particles into the bearing unit.

3. MODEL STUDY CONCEPTION

The aim of the study is new structure two-shaft multi-purpose shredder creation, use for wide range raw materials crushing and inclusion in the recycling process. For designing the basic unit of the machine – the crushing chamber and the shredding shafts, the following data is used:

- Maximum compressive strength of the destructed elements: 55 MPa;
- Approximate dimensions of the chamber neat area: 900 x 700 mm;
- Feeding of the shredder: flow, discrete, controlled by an operator;
- Crushed material separation and loading: flow, continuous, automatic;

- Metal particles separation in the crushed material: flow, continuous, automatic, with magnetic boards;
- Hydraulic machine operated by a pump or hydraulic motors cylinders and internal combustion engine/ electric motor;
- Approximate operated power: 210 kW.

After investigating and analyzing on the possibilities of specialized software programming systems, which are optimal for solving such type of problems, our attention was drawn to using particular method. In this method the structure is divided into a finite number of elements, as described is the behavior of each separate element, involved in the formation of a unit. As a result of this process was obtained algebraic equations system, which in the task for stress analysis represents equations for static balance of the units. Depending on the geometry and the assumptions used for building the model, the finite elements may be divided into:

- Linear (one-dimensional): straight lines or curves along the length of the element;
- Planar (two-dimensional): triangular or quadrangular, the sides of which may be straight lines or curves, in dependence on the number of the units in them;
- Spatial (volumetric): tetrahedron or parallelepiped, the walls of which may also be with straight or curved surfaces.

The obtained results quality depends on the discretization, as with sizes reducing of the finite elements (which mean an increase in their number in a given area), accuracy increases, but the equations number for solving also increases. Accuracy is also influenced by the shape of the finite elements.

The investigations of the mechanical load and behavior of the crushing chamber and shredding shafts have been conducted through solving the equations, describing the mechanical processes in working conditions by method of the finite elements. For this aim have been generated three-dimensional geometric models of the chamber lower part (fig. 3) and the shredding shafts (fig. 4), which are discretized on a planned network of finite elements in the programming environment of ANSYS MECHANICAL APDL.

The pressure, which each carbide cone on the cogs of the disk exerts on the destructed concrete railway sleeper, is 94 MPa, which is nearly two times larger than the destruction stress of 55 MPa.

The disruptive pressure has been adopted as applied on an area of the con with diameter 30 mm. It is transformed into radial forces on the knives, respectively torques, on the shredder shafts. With accepted condition for three simultaneously working "destructive" cons, there is determined the rotation nominal moment of each shaft for 25 revolutions/min. - 40 kN.m. In this case, the appropriate heliocentric-type reducer is PG 5001, with gear ratio $I = 5,1$. Accordingly, the driving hydraulic motor is radial piston with constant flow, type IAM.1600 H, with maximum revolutions 250 min^{-1} and rotation moment equal to 7860 N.m, at a 300 bar pressure.

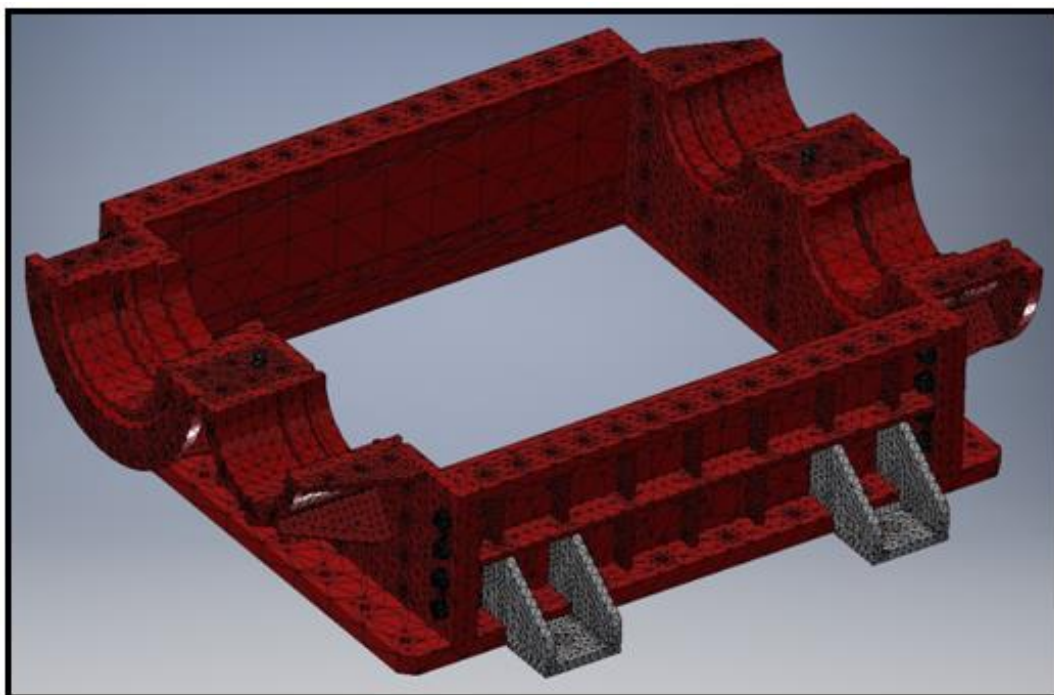


Fig. 3. Crushing chamber, presented by the finite elements method

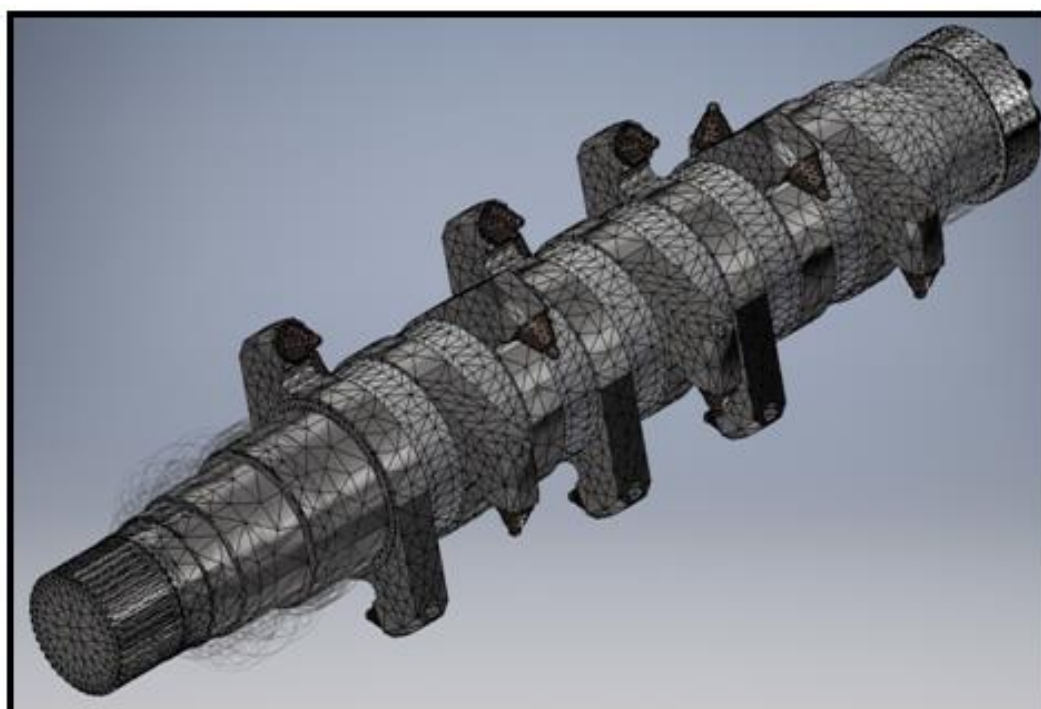


Fig. 4. Shredding shaft, presented by the finite elements method

The end conditions, reflecting the mechanical stress during operation of the steel structure, include the following parameters:

- Input power: $P_{\text{inp}} = 90 \text{ kW}$;
- Working shaft revolutions: $n_v = 25 \text{ min}^{-1}$;
- Working shaft rotation frequency: $\omega_v = \frac{\pi \cdot n_v}{30} = 2,62 \text{ rad/s}$;
- Working shaft rotation moment: $M_v = \frac{P_{\text{sk}}}{\omega_v \cdot \eta} = 35 \text{ kN.m}$, where $\eta = 0,98$ is transmission efficiency coefficient;
- Concrete destruction stress: $\tau_s = 60 \text{ MPa}$;
- Shear force from one knife: $F_s = \frac{M_v}{3,0,175} = 66,7 \text{ kN}$;
- Crushing resistance moment from one knife: $M_{s1} = F_s \cdot l_s = 11,67 \text{ kN.m}$.

The required propelling power W of the shredding shafts is determined on the basis of the formula:

$$W = \frac{P_b \cdot \mu \cdot S_t \cdot \frac{D_t}{2} \cdot Z \cdot N_v}{9554} = \frac{55 \cdot 10^6 \cdot 2 \cdot 6 \cdot 10^{-4} \cdot 0,15 \cdot 8 \cdot 25}{9554} = 207 \text{ kW}$$

where: P_b is the concrete railway sleepers destruction stress: 55 MPa;

S_t – maximum contact area of each destructive con $\sim 20 \times 30 \text{ mm}$ or $6 \cdot 10^{-4} \text{ sq.m (m}^2\text{)}$;

Z - number of simultaneously working disks 8 (4 from one shaft and 4 from the other shaft), with total length along the shafts axis 320 mm, which is greater than the railway sleepers maximum dimension 300 mm;

D_t – cutting disks diameter 300 mm (distance of the cons from the shaft axis);

N_v – shafts revolutions 25 min^{-1} ;

μ – power reserve coefficient, equal to 2.

The shredding shafts are mounted on the side of the reduction gears in paired roller radial axial bearings, and on the other side – in needle-roller bearing with inner ring. The shredding shafts structure is verified for total strength (tension, compression, torsion), as applied are the loads from the shaft weight, the knives with the destructive cons, and the intermediate disks, as well as the support reactions in the shafts bearings. The investigations have been conducted by the described below mathematical models and procedures. The equations system has been solved with steel parameters, presented in Table 1.

4. RESULTS AND DISCUSSION

The mechanical load during structure operation is presented on fig. 5.

In Table 1 are shown summarized results of the chamber strength verification with the adopted steel mechanical properties.

Table 1. Summarized results of the chamber strength verification

Name	Steel	
General	Mass Density	7,85 g/cm ³
	Yield Strength	207 MPa
	Ultimate Tensile Strength	345 MPa
Stress	Young's Modulus	210 GPa
	Poisson's Ratio	0,3 ul
	Shear Modulus	80,7692 GPa
Stress Thermal	Expansion Coefficient	0,000012 ul/c
	Thermal Conductivity	56 W/(m K)
	Specific Heat	460 J/(kg c)

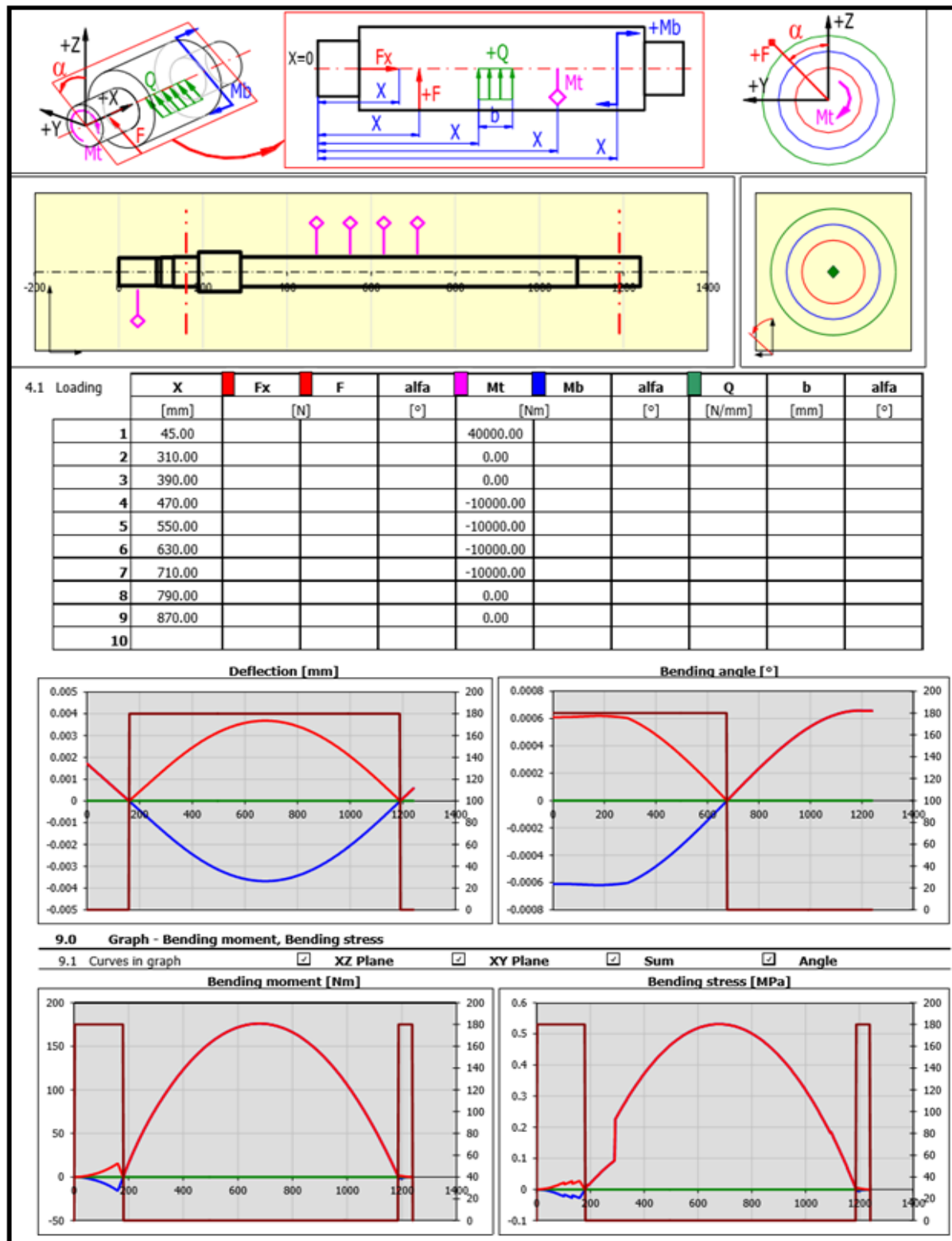


Fig. 5. Mechanical load during operation

Figures 6, 7 and 8 are presented visualization of basic parameters, characterizing the stress state of the steel structure.

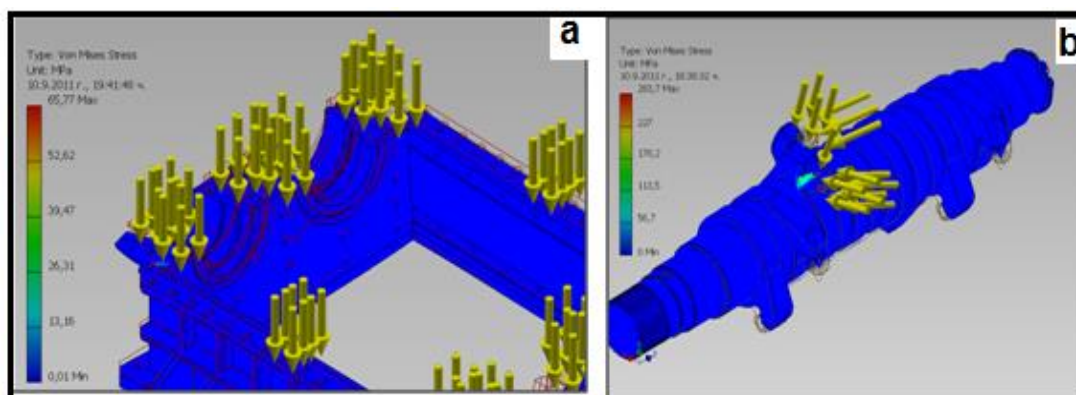


Fig. 6. Summarized stresses

a) in the crushing chamber elements; b) in the shredding shafts elements.

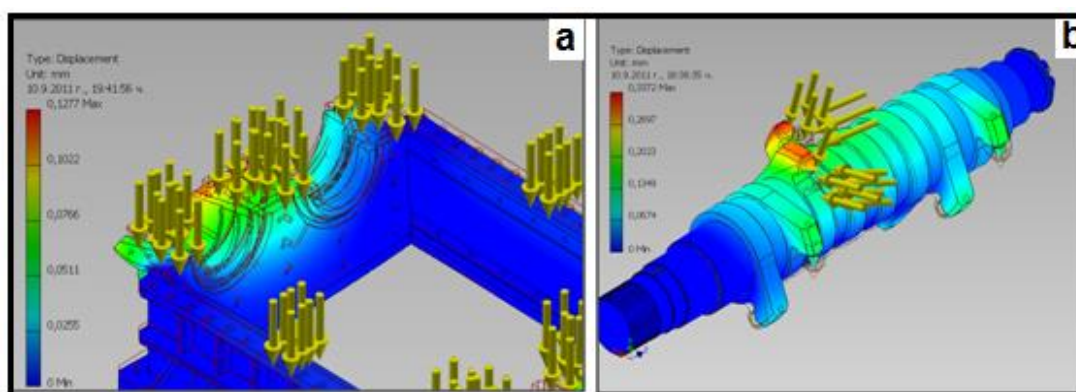


Fig. 7. Maximum deformations

a) of the crushing chamber elements; b) of the shredding shafts elements

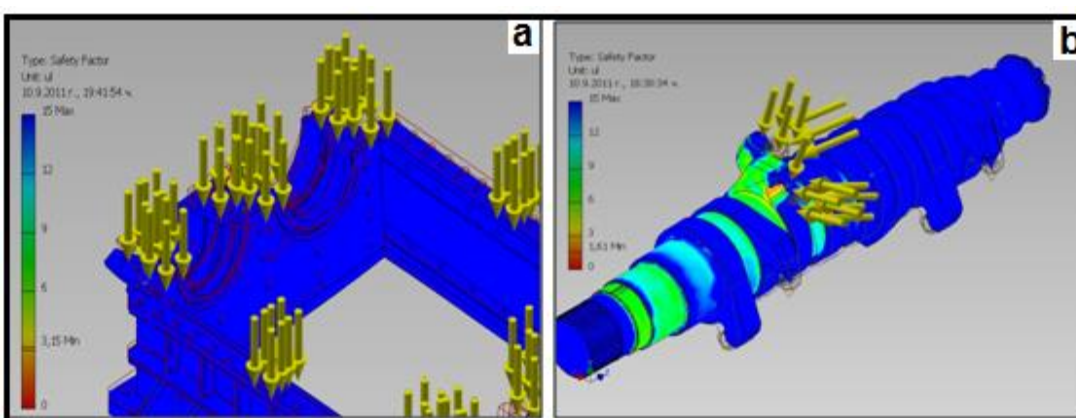


Fig. 8. Safety factor

a) for the crushing chamber elements; b) for the shredding shafts elements

In Table 2 are shown summarized results the maximum and minimum stresses and deformations, and Table 3 determines the support reactions.

Table 2. Maximum and minimum stresses and deformations

Name	Minimum	Maximum
Volume	39292300 mm ³	
Mass	308,444 kg	
Von Mises Stress	0,00548071 MPa	65,7722 MPa
1st Principal Stress	-15,6595 MPa	28,8686 MPa
3rd Principal Stress	-83,2857 MPa	4,36874 MPa
Displacement	0 mm	0,127705 mm
Safety Factor	3,14722	15

Table 3. Support reactions

Constraint Name	Reaction Force		Reaction Moment	
	Magnitude	Component (X,Y,Z)	Magnitude	Component (X,Y,Z)
Pin Constraint:1	90793,5 N	-90786,3 N	5917 N m	-73,9095 N m
		-1143,34 N		-5916,54 N m
		0 N		0 N m
Pin Constraint:2	0 N	0 N	4082,63 N m	-182,663 N m
		0 N		-4078,55 N m
		0 N		0 N m
Pin Constraint:3	49891,2 N	-49522,2 N	12149,7 N m	1378,84 N m
		6057,02 N		12071,2 N m
		0 N		0 N m
Pin Constraint:4	20872,4 N	20871,4 N	16536,2 N m	-21,0458 N m
		-207,16 N		238,686 N m
		0 N		16534,4 N m

The study results show that the maximum stresses for the examined structure do not exceed the permissible values for the chamber material and for the shafts material.

5. CONCLUSIONS

The shredder selection for concrete railway sleepers crushing, according to the obtained results from the calculations, is done constructively and economically. From great importance are the type of the used reduction gears and their drive.

For single-shaft shredder driving, the required power should be ensured from one reduction gear. It have to be with power $P_v = 207,2$ kW, which suggests large sizes and complicated drive. For propelling of each four shafts of a four-shaft shredder, the required power should be ensured by four reduction gears. They should have power $P_v = 49,5$ kW. For the used four reduction gears there are needed four drives, which suggest complicated and expensive structure.

Two-shaft shredder is the optimal combination of structural and economic parameters. For driving of each two shafts are needed two reduction gears, each with power $P_v = 103,6$ kW. The proposed modeling approaches allow detailed assessment of the crushing machine elements, under various load conditions.

As a result of studies carried out an analysis of the operation principle, the different types of shredders basic parameters, their advantages and disadvantages, as well as their application have been made. Proposed is a shredder for concrete railway sleepers crushing, according to the main criteria for crushing machine selection. The research indicates that the examined structures of the crushing chamber and the shafts may be used for shredders crushing machines.

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