Proc. Estonian Acad. Sci. Engin., 1996, 2, 1, 36–48

https://doi.org/10.3176/eng.1996.1.05

UTILISATION OF INDUSTRIAL METAL SCRAP BY MECHANICAL MEANS

Priit KULU, Aleksei TÜMANOK, and Valdek MIKLI

Tallinna Tehnikaülikooli materjalitehnika instituut (Department of Materials Technology, Tallinn Technical University), Ehitajate tee 5, EE-0026 Tallinn, Eesti (Estonia)

Received 12 December 1995, accepted 3 April 1996

Abstract. This paper focuses on the disintegrator milling technology, used for mechanical treatment of metal chips (cast iron, alloy steels, and non-ferrous alloys). The study centered on the types of disintegrators (laboratory and semi-industrial) and milling technologies (direct and separative) for metal chips and wastes. A technology of mixing and homogenisation of powder mixtures is described. Due to high velocities in disintegrators (up to 300 m/s) and high stresses operating during grinding, an additional effect of mechanical activation of ground material was observed, and attempts were made to exploit it in the technological processes. Applications of the produced metal powders in powder metallurgy and surface technology were investigated. Such applications as low-alloyed steel powders for powder metallurgy parts, non-ferrous metal alloy powders for solid zincification and brassing, and powders for new composite powder coatings are discussed.

Key words: utilisation of metal chips, disintegrator milling technology, grindability, metal powders, powder metallurgy, mechanical coating, protective coatings.

1. INTRODUCTION

In the contemporary mechanical engineering industry, the demand and the prices of raw materials are increasing. Saving of the existing resources and recycling of materials are topical issues.

The circulation of metals assumes formation of various kinds of metal scrap (metallurgical, industrial, and old) and waste metal [1].

The metallurgical industry is practically absent in Estonia, the domestic metallurgical scrap from casting and rolling is minimal. The amount of industrial scrap (formed in the process of final product manufacturing) is high because of low-quality production technologies. Utilisation of this scrap, in particular, chips of alloyed steels and non-ferrous metals in process metallurgy, is irrational because then we burn alloying elements. Exporting is disadvantageous because of their small volume density and low prices. Thus, industrial scrap (e.g., chips of ferrous and non-ferrous metals and alloys) is dominant in Estonia.

To utilise industrial metal scrap, mainly mechanical methods have been used. First of all, by the collision method, metal chips were milled. Disintegrator is one of the few devices which treats materials by collision [2, 3]. Based on our long-term experience and theoretical studies of milling, DS-series of disintegrators were developed, operating in the conditions of direct, separative, selective, and selective-separative milling. Besides milling, as a result of high intensity collisions, the effect of the mechanical activation of the ground material is important.

Based on the disintegrator milling technology, utilisation of the following metal chips was studied:

a) cast iron;
b) low- and high-alloy steels;
c) non-ferrous alloys: aluminium–copper, zinc–aluminium, and copper–zinc alloys.

2. EXPERIMENTAL METHODS

2.1. Initial materials

Metal and alloy chips, applied in the metal working industry in Estonia, were used as the initial materials. First of all, the alloys which produce crushable chips in the processes of machining (milling and turning) were chosen. Otherwise, the pretreatment of long plastic chips is necessary.

Table 1 shows the composition and mechanical properties of the materials studied. Before grinding, the chips were washed in petrol, dried about fifty hours at room temperature and heated for two hours at 150 °C.

Table 1

The initial materials

Type and designation of materials	Content of elements, %	Mechanical properties, min		
		σ_B, MPa	δ, %	HB
Grey cast iron (СЧ15)	3.5–3.7 C 2.0–2.4 Si 0.5–0.8 Mn base – Fe	80–220	0	130–240
Zn–Al-alloy ZnAl4 (ЦАМ4-1)	3.5–4.3 Al 0.75–1.25 Cu base – Zn	333	10	91
Cu–Zn-alloy CuZn40Pb (ЛС59-1)	59.0–61.0 Cu 0.6–1.0 Pb remain – Zn	340–470	25	100
Al–Cu-alloy AlCu5 (Д16)	3.8–4.9 Cu 1.2–1.8 Mg base – Al	392	8	90

2.2. Grindability of metal chips

Metal chips were ground in the disintegrator mill DSL-160 by direct and separation milling at the rotation velocities from 2000 to 10 000 rpm. The velocities between impact elements of the disintegrator and the particles of grinding material ranged from 30 to 150 m/s. The milling step was analysed by the granulometric method.

To achieve metal powders with the determined granulometry, chips were ground at various rotation velocities (2000, 4000, 6000, 8000 and 10 000 rpm). In the direct grinding, to achieve the necessary fraction, multi-stage grinding was used. To estimate grindability, the parameter of grinding-specific energy of grinding, was used (Table 2) [2, 3].

Table 2

Maximum velocity of collision and specific energy of treatment E_0 of material with DSL-160 in dependence on velocity of rotation of rotors and multiplicity of treatment

Rotation velocity of rotors, rpm	Maximum velocity of collision, m/s	Specific energy of treatment E_0,kJ/kg, by multiplicity of treatment			
		1	2	3	4
2000/2000	32	0.8	1.6	2.4	3.2
4000/4000	64	3.1	6.2	9.3	12.4
6000/6000	96	7.0	14.0	21.0	28.0
8000/8000	128	12.4	24.8	37.2	49.6
10 000/10 000	160	19.4	38.8	58.2	77.6
10 000/9000	151	17.3	24.6	51.9	69.2
10 000/8000	142	15.2	30.4	42.6	60.8

2.3. Granulometry and morphology of a ground product

To study the granulometry of a ground product by the granulometric analysis, the modified Rosin–Rammler distribution function and the method were used [4].

The granulometry of a ground product was described by Rosin–Rammler in the logarithmic size of particles

$$x = \log_k \frac{X_0}{X}, \qquad (1)$$

where

x – natural size of particles, mm;

X_0 – upper limit of possible size of particles of the material studied;

k – coefficient (ratio) of sieves system used in the experiments ($k = 2$, 2^5, 2^{25}).

In our experiments, $k = 2$ was used. The modified Rosin–Rammler distribution function was applied in the form

$$f_m(x, x_0, m, n) = \frac{n-1}{m} Z^{n-1} \exp\left(-\frac{n-1}{m} Z^n\right) \quad (2)$$

in the differential form and in the integral one

$$F_m = 1 - \exp\left(-\frac{n-1}{n} Z^n\right), \quad (3)$$

where Z is an auxiliary variable

$$Z = \frac{x - x_0}{m}. \quad (4)$$

Parameters of distribution are shown in Fig. 1.

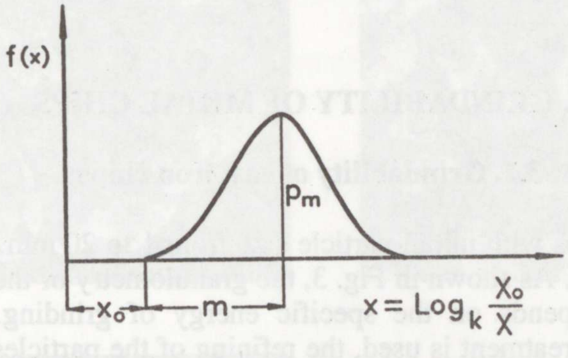

Fig. 1. The principal parameters of the used distribution function: $x_0 + m$ – the logarithmic size of the particle with maximum probability, p_m – value of maximum probability, X_0 – upper limit of largest particle, m – mode of distribution.

Unfortunately, the distribution function cannot be expressed through p_m directly. Instead of p_m, in (2) and (3), the auxiliary parameter n is used. Parameter p_m is expressed by

$$p_m = \frac{n-1}{m} \exp\left(-\frac{n-1}{n}\right). \quad (5)$$

The expression $m \times p_m$ is the function of n only and is represented in Fig. 2. The dependence of p_m on n is nearly linear.

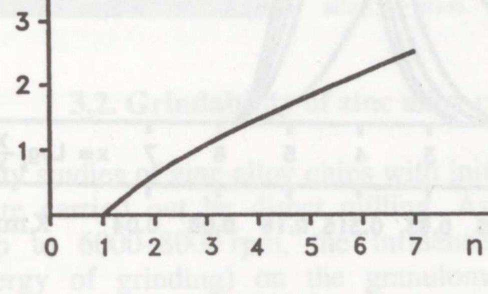

Fig. 2. Dependence of parameter p_m on auxiliary parameter n.

In addition, for the metallographical analysis, stereological methods were used to characterise the morphology of metal powders. The distribution of particle sizes (medium diameter and area) was determined, and formfactor of particles was calculated.

2.4. Technological properties of metal powders

The technological properties of metal powders (bulk density and flowability) were determined by standardised methods. In the process of grinding, the hardening of particles was determined by measuring the lattice parameter by X-ray analyzer DRON-2.

To determine the specific surface area of a powder by the method of thermal desorption of nitrogen, a modified equipment SORBTOMETER EM-31 was used.

3. GRINDABILITY OF METAL CHIPS

3.1. Grindability of cast iron chips

Cast iron chips with initial particle size from 1 to 20 mm were ground by direct milling. As shown in Fig. 3, the granulometry of the ground cast iron (СЧ15) depends on the specific energy of grinding. When low specific energy treatment is used, the refining of the particles depends on the direct fracture of initial chips because the number of impacts (cycles) is low.

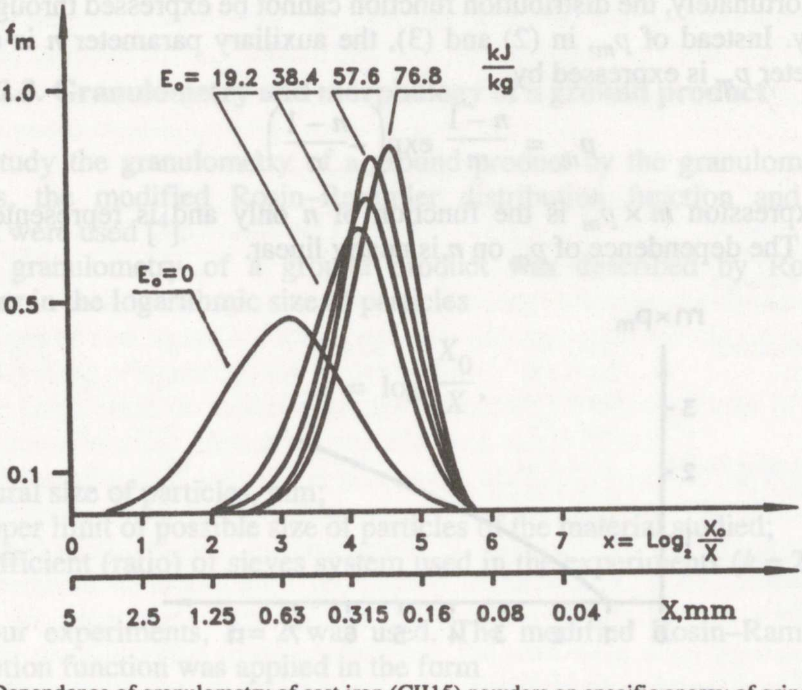

Fig. 3. Dependence of granulometry of cast iron (СЧ15) powders on specific energy of grinding E_0.

By multi-stage grinding after each grinding, a new finer fraction results. This fine product is the result of the direct fracture of particles, and it can be used in powder technology. Figure 4*a* illustrates the shape and microstructure of cast iron powders ground at optimal parameters.

a

b

c

Fig. 4. Particles shape and microstructure of ground powders: *a* – cast iron, *b* – zinc alloy, *c* – brass.

3.2. Grindability of zinc alloy chips

Grindability studies of zinc alloy chips with initial particle size from 1 to 8 mm were carried out by direct milling. As shown in Fig. 5*a*, at velocities up to 6000–8000 rpm, the influence of rotation velocity (specific energy of grinding) on the granulometry (particle size) is considerable. The same was observed with multi-stage grinding, i.e., the fineness of ground product increased noticeably, up to 3–4 times; further grinding did not increase the powder fineness so much (Fig. 5*b*).

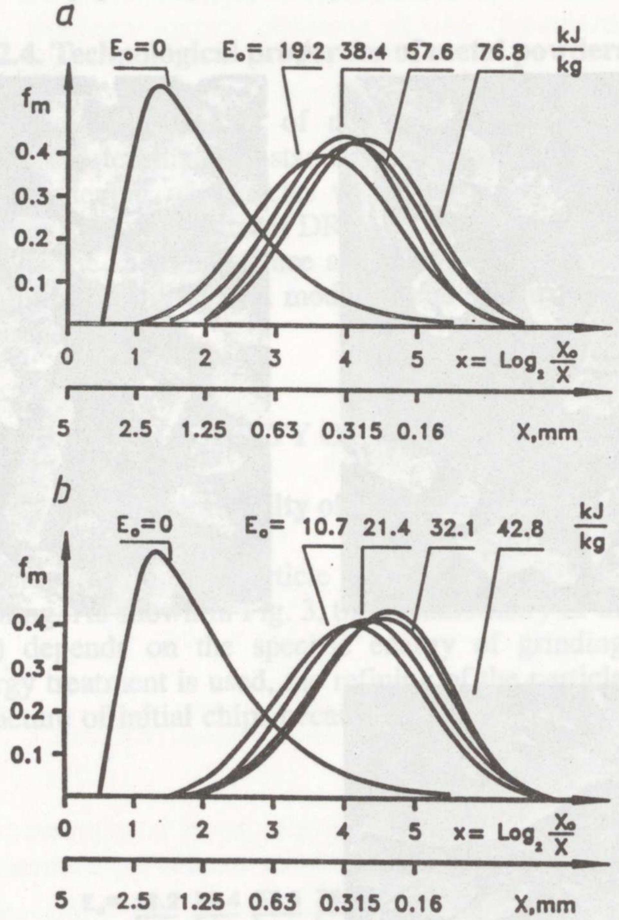

Fig. 5. Dependence of granulometry of ZnAl powder on specific energy of grinding E_0 by velocities of revolution of rotors: *a* – 8000/8000 rpm, *b* – 10 000/10 000 rpm.

As shown in Fig. 6, the medium size of particles (X/X_0) and the ratio of specific surface areas of the ground product and initial chips (A/A_0) comply with the specific energies of grinding at various grinding parameters.

Table 3 demonstrates the bulk density of multi-stage ground zinc alloy powders.

Table 3

Bulk density of multi-stage ground powders

Multiplicity of grinding	Initial chip	1	2	3	4	5
Bulk density, g/cm^3	0.73	1.78	2.31	2.60	2.71	3.07

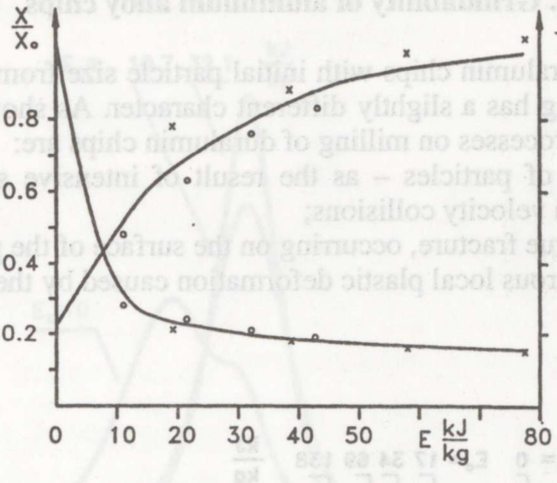

Fig. 6. Dependence of ratio of median size X to initial median size X_0 and ratio of specific area A to its initial value A_0 on specific energy of grinding.

An optimal granulometry (160–320 μm) of zinc alloy powders, used in the coating technology, was obtained by grinding at the rotation velocities 6000–8000 rpm after 3–4 time grinding. The output of suitable fraction was about 40–50%. Higher fineness or output of fine powders can be achieved by separation grinding. Figure 4*b* illustrates the shape and microstructure of zinc alloy powders ground at optimal parameters.

Table 4 demonstrates the technological properties of zinc alloy powders used in the following solid zincification.

Table 4

The technological properties of zinc alloy powders

Grain size, μm	Bulk density, g/cm^3	Strewing density, g/cm^3	Flowability, g/s
160	3.9	3.8	1.2
315	3.5	3.4	1.6

As a result of X-ray investigations of non-ground chips and ground powders, the effect of cold hardening of the particles due to the impact grinding was found, the difference in crystal lattice parameters was about 5–10% (Table 5).

Table 5

The parameters of crystal lattice of zinc alloy chips and powders

Stage of the material	Lattice parameter, nm
Zinc alloy chip	
– initial stage	0.2665
– annealed (200°C, 30 min)	0.2664
Ground powder (4× at 8000 rpm)	0.2495

3.3. Grindability of aluminium alloy chips

Refining of duralumin chips with initial particle size from 5 to 20 mm by impact grinding has a slightly different character. As shown in Fig. 7, the two parallel processes on milling of duralumin chips are:

1) direct fracture of particles – as the result of intensive stress waves, originated by high velocity collisions;

2) low cyclic fatigue fracture, occurring on the surface of the particles – as the result of numerous local plastic deformation caused by the collisions.

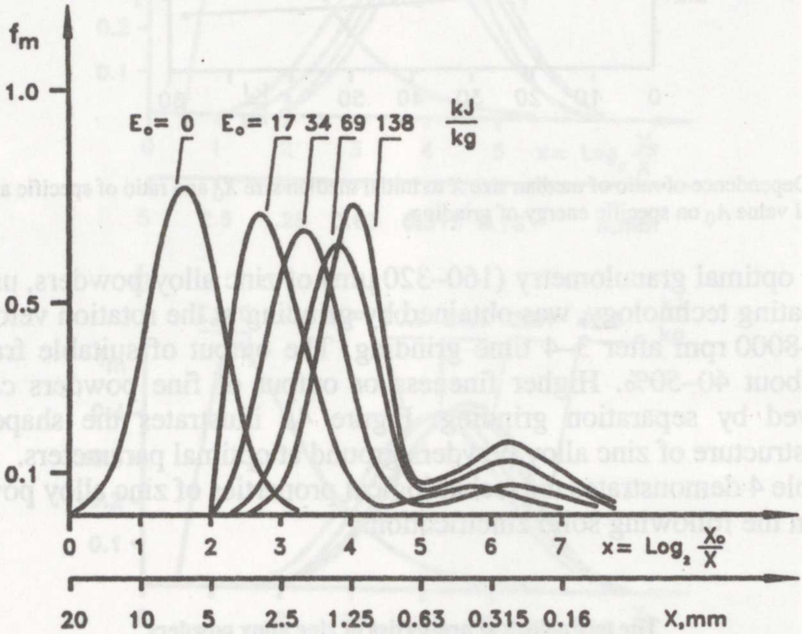

Fig. 7. Dependence of granulometry of duralumin powder on specific energy of grinding E_0.

The fine fraction (0.16–0.315 mm), the product of low cyclic fatigue fracture, is primarily suitable for powder metallurgy, but all the particles are cold hardened, and the powder needs annealing before use.

3.4. Grindability of copper alloy chips

Copper–zinc alloy – brass chips with initial particle size of about 0.2–1.5 mm were subjected to multiple direct grinding.

As shown in Fig. 8 and confirmed by a rule of milling of plastic materials, considerable refining takes place after first grinding. During the following grindings, the material is not furtherrefined. To achieve a finer fraction, the multi-stage grinding with cycle numbers more than 10–20 is necessary. As a result, the fatigue process will take place and the fine fraction becomes available. Figure 4*c* illustrates the shape of brass powder ground at optimal parameters.

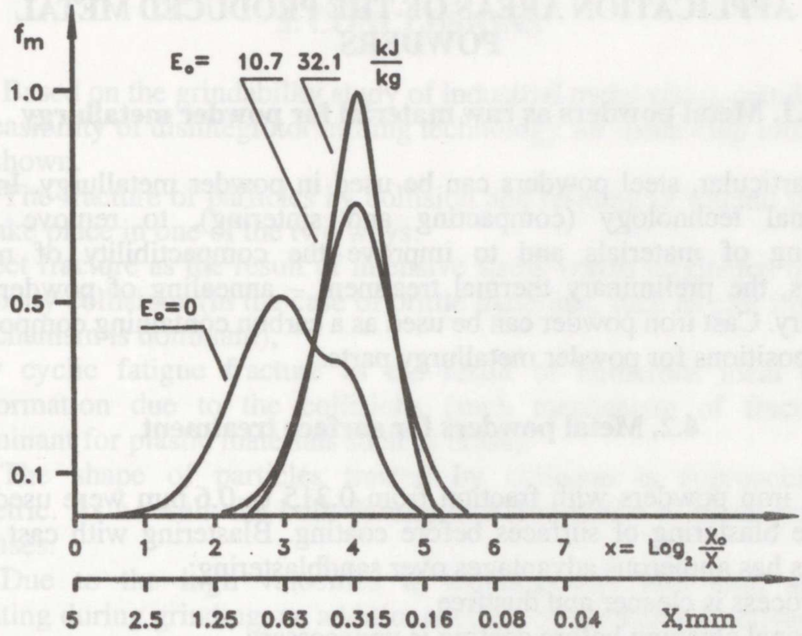

Fig. 8. Dependence of granulometry of brass powder on specific energy of grinding E_0.

3.5. Morphology of ground product

The results of the morphology study of the produced powders are illustrated in Table 6. The microstructures of cast iron, zinc, and copper alloy powders are shown in Fig. 4. The particles have mainly isometric form except brass powder. The size and shape of initial chips was practically unchanged after the fourth grinding.

Table 6

The main characteristics of ground metal powders with determined granulometry from 0.160 to 0.315 mm

Material	Granulometry			Form factor k_F	
	Main fraction, μm and this %	d_m, μm	A_m, μm^2	Main fraction	Medium
Grey cast iron	60–180 75	110	9000	0.65	0.61
ZnAl4	70–220 75	130	12000	0.75	0.67
CuZn40Pb	60–270 85	140	15000	0.65	0.63
AlCu5	30–100 85	80	5100	0.80	0.72

4. APPLICATION AREAS OF THE PRODUCED METAL POWDERS

4.1. Metal powders as raw material for powder metallurgy

In particular, steel powders can be used in powder metallurgy. In the traditional technology (compacting and sintering), to remove cold hardening of materials and to improve the compactibility of metal powders, the preliminary thermal treatment – annealing of powders, is necessary. Cast iron powder can be used as a carbon containing component in compositions for powder metallurgy parts.

4.2. Metal powders for surface treatment

Cast iron powders with fraction from 0.315 to 0.6 mm were used for abrasive blastering of surfaces before coating. Blastering with cast iron particles has numerous advantages over sandblastering:
– the process is cleaner and dustfree,
– additional cleaning before coating is unnecessary.

4.3. Non-ferrous metal powders for mechanical coating

Due to its chemical and physical properties, zinc is a widespread and the cheapest non-ferrous metal for surface treatment. The galvanical and gas-thermal (gas-flame and electric arc spraying) zincification are widely used in protection against corrosion, but the method of solid zincification (sherardisation) is equally prospective [5].

Based on the study of zincification process, using zinc alloy powder, optimal parameters of the process were elaborated [6]. The difference in the thickness of zinc coatings, obtained by zincification in zinc alloy and pure zinc powders (in the first case, the thickness of the coatings is 2–3 times smaller), caused by the Al, contained in the zinc alloy powder. According to literature, Al in zincification mixture increases the corrosion resistance of zinc coatings [7].

Solid zincification has advantages over other methods (the process is simple, dry and environmentally friendly, the coatings have a complex structure and properties, and are compatible the coatings). Therefore at first this method is very attractive in small production and for covering of powder metallurgy parts.

To increase the corrosion resistance of mechanical Zn-coatings, the zincing-aluminising in the mixture of Zn- and Al-content components (ratio 55:45%) was used, and the process of solid zincing-aluminising was studied.

The technology of solid brassing in the mixture of brass powder and glass balls for decorative copper-based coatings on aluminium alloys is under investigation.

5. CONCLUSIONS

1. Based on the grindability study of industrial metal scrap, metal chips, the feasibility of disintegrator milling technology for metal chip utilisation was shown.

2. The fracture of particles by collision and refining of ground product can take place in one of the two ways:
- direct fracture as the result of intensive stress waves originated by high velocity collisions (in the case of brittle materials, such as cast iron, this mechanism is dominant);
- low cyclic fatigue fracture as the result of numerous local plastic deformation due to the collisions (such mechanism of fracture is dominant for plastic materials such as brass).

3. The shape of particles treated by collision is approaching to isometric. As a result, the bulk density and flowability of metal powders increases.

4. Due to the high velocities in disintegrators and high stresses operating during grinding, an additional effect of mechanical activation of the ground material is observed, which influences in two different ways:
- worsening compactability of powders;
- activating diffusion processes in the following technological processes.

5. The produced powders (cast iron and steel powders for powder metallurgy parts, zinc, aluminium and copper alloy powders for mechanical coating) can be used as raw material in powder technology.

REFERENCES

1. Taptik, Y., Aydin, S., and Arslan, C. Metal recycling activities and its economics in developing countries. A case study. – Proc. of the 1994 Conference on the Recycling of Metals. ASM International Europe, Amsterdam, 1994, 183–190.
2. Tymanok, A. Specific Energy of Collision and of Material Treatment in Disintegrator. Tallinn, 1981 (Russian). Deposited in VINITI (Ljubertsõ Institute of Technical Information) N 2957-81 Dep.
3. Tymanok, A. Estimation of Cinematic Parameters and of Rational Number of Grinding Bodies in Disintegrator. Tallinn, 1984 (Russian). Deposited in Library of Technical Information Tallinn, N1E-D84.
4. Tymanok, A. and Tamm, J. The rational empirical distribution function for describing the granulometry of ground product. – Proc. Siberian Acad. Sci. Chem. Ser., 1983, **6**, 8–11 (Russian).
5. Evans, D. R. Sherardizatsiya. Metallurgiya, Moskva, 1988 (Russian).
6. Kulu, P., Tymanok, A., Kudryavtsev, V., and Kozyakov, V. Treatment of metal wastes by mechanical and chemical means. – Proc. of the 1994 Conference on the Recycling of Metals. ASM International Europe, Amsterdam, 1994, 375–382.
7. Kulu, P., Tymanok, A., and Kalamees, K. Solid zincification of compact and powder steels. – Trans. Tallinn Techn. Univ. Powder Materials and Coatings, 1994, No. 741, 3–15.

TÖÖSTUSLIKE METALLIJÄÄTMETE MEHAANILINE UTILISEERIMINE

Priit KULU, Aleksei TÜMANOK, Valdek MIKLI

Tööstuslike metallijäätmete utiliseerimise eesmärgil on uuritud nende töötlemist mehaanilisel, s.o. desintegraatorjahvatuse teel. Metallilaastu (malm, legeerteras, värvilissulamid) jahvatamiseks on kasutatud mitut tüüpi desintegraatorseadmeid (laboratoorseid ja pooltööstuslikke sealhulgas desintegraatorit DSL-160) ja tehnoloogilisi variante (otse- ja separatsioonjahvatust).

Suurest kiirusest tulenevalt desintegraatoris (kuni 300 m/s) ja jahvatatava materjali kõrge deformatsioonipinge tõttu on kõrvuti peenenemisega täheldatav jahvatusprodukti mehaanilise aktiviseerumise efekt, mida võib kasutada järgnevates tehnoloogilistes protsessides.

On selgitatud ka saadud metallipulbrite kasutusvõimalusi pulbermetallurgias ja pinnatehnoloogias. Positiivseid tulemusi on saadud madallegeerterase pulbrite kasutamisel pulbermetallurgias konstruktsioonidetailide valmistamiseks, värvilissulamite (tsingi- ja vasesulamid) pulbrite kasutamisel mehaaniliseks pindamiseks ja uute pulberkomposiitide loomiseks.