TURBO-ABRASIVE FINISHING

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Introduction:

Mass finishing of complex part shapes is one of the most challenging problems facing manufacturers today. Many parts are manually deburred and finished because of their complex geometric forms. This labor intensive manual handling and finishing of parts and components has had a negative impact on manufacturing process productivity and the uniformity of surface finish quality.

A relatively recent development, TURBO-ABRASIVE technology for part finishing or machining, which utilizes free abrasive grain, has proven to be a cost effective and efficient alternative to manual finishing of complex part shapes. TURBO-ABRASIVE finishing or machining (TAM) offers an economical and environmentally friendly method for mechanizing, automating and simplifying finishing operations which until now required manual deburring and/or finishing. Additionally, the TAM finishing method offers surface finishes that are substantially improved when compared with manual or less advanced finishing procedures.

The technology for Turbo-Abrasive finishing of complex part shapes (TAM - technology) was an outgrowth of research and development by the author of this paper and was carried out in collaboration with Dr. Z. Kremen in St. Petersburg, Russia in the mid 1970's. The above mentioned technology has a number of advantages in comparison with several other mechanical finishing processes (such as conventional spindle finishing or abrasive flow machining). Some of these advantages are:

- High flow of free abrasive grain allows for penetration of abrasive media particles to all difficult to access regions of the part to perform finishing operations thereon.
- Low energy consumption;
- Simplicity of equipment and operation;
- Combination of sufficiently high rate of metal removal with improved physical and mechanical properties of metal surfaces.

The new technology provides the solution for a number of surface finishing problems that can not be efficiently processed by conventional methods and so far have required significant use of skilled manual labor.

Turbo-Abrasive Finishing Background. Turbo-Abrasive machining implies that the part is placed inside a specially designed
Typical complex parts effectively finished by TAM technology
chamber in which there is a suspended and fluidized bed of free abrasive grain. The fluidized bed of abrasive media particles is of low viscosity and high fluidity; the mode and amount of rotational movement that is given to the part to be processed, within this fluidized media bed, depends on its configuration and final finish requirements.

Analysis has shown that such media particles can be used as an unusually useful and versatile abrasive tool. While the part is rotating in a fluidized bed of abrasive grain, metal removal, deburring, radius formation, and micro-relief of part surface texture are developed from high speed collision and interaction of abrasive grain and part surfaces.

The magnitude of metal removal is determined by a number of factors including: the amount of media particle pressure generated on the surface and by high frequency and density of particles and part surface collisions approaching \((3-5) \times 10^4 \text{ L/s/mm}^2\). The calculations carried out by formula (1) have shown that

\[
V(\text{min}) = 3*o*t/\pi*(k+1)*[d*Rp*(1/Ea+1/Em)]^2, \quad (1)
\]

where,
- \(o\) - metal fluidity limit;
- \(t\) - contact time (abrasive and surface);
- \(k\) - recovery coefficient;
- \(d\) - abrasive grain density;
- \(Rp\) - medium radius of grain projection;
- \(Ea, Em\) - elasticity modula of abrasive grain and metal

the minimum speed of interaction required for starting of metal plastic deformation on components made of constructional steel and ground by abrasive particles with dimension equal to \(D_g = 160 - 630 \mu m\) is \(V_{\text{min}} = 1.42 - 0.83 \text{ m/sec}\). Thus only media particle movement within the fluidized bed at a speed equal to 0.1 - 0.5 m/s is insufficient for effective treatment. That is why it is required to impart to the component being processed additional velocity that is achieved either by rotational movement or high-frequency oscillation. With the increase of peripheral speed of a part the force action of a device (i.e. fluidized bed of abrasive grain) on the surface being machined significantly increases, thus intensifying metal removal and microrelief formation. Abrasive particle pressure value calculated by formula (2) shows:

\[
P(fd) = (k+1)*[d*(1-\epsilon)*(V_g+V_p*sin\theta*sin\beta)]^2, \quad (2)
\]

where,
- \(1-\epsilon\) - abrasive grains concentration on a unit volume of fluidized bed;
- \(V_g\) - speed of abrasive grain movement;
Model TAY-500 Turbo-Abrasive Finishing Machine
Vp - speed of a part movement;
0 - angle of sides inclination of microunevennesses;
B - angle between the direction of microunevennesses and part speed vector;

interaction of main technological factors of Turbo-Abrasive machining process, including: abrasive grain parameters f, Dg; fluidized bed parameters e, Vg; kinematic parameters Vp; surface roughness parameters 0, B and mechanical parameters k, of surface being machined.

Calculations show that with a change of Vp from 10 m/sec till 25 m/sec the values of P(fd) are equal to 0.1 - 0.5 MPa. Grain pressure value on a surface being machined or finished varies considerably depending on the surface orientation in relation to the fluidized bed of abrasive particles. The optimum surface disposition increases P(fd) value 1.2 - 2.6 times; the process productive capacity figures grow respectively.

A study of mark tracks of single particles illustrates that the length of mark scratches grows considerably after rotational speed of the part is increased (Figure 1). So if with an immobile part the medium length of scratch Lm when grinding by silicon carbide particles with a dimension of grain (Dg) = 630μm is 8μm then at speed Vp = 5m/sec Lm = 19.8μm, at speed V = 10m/sec Lm = 36.6μm, and at speed V = 15m/sec Lm = 57μm.

The average number of scratches are:

at immobile part Nm = 4-5 1/mm^2 sec;
at rotational part Vp = 5m/sec, Nm = 38 1/mm^2 sec;
Vp = 10m/sec, Nm = 75 1/mm^2/sec;
Vp = 15m/sec, Nm = 154 1/mm^2 sec.

Thus the transition from immobile part grinding to grinding the part revolving at the rate of 15 m/sec increases the productive capacity of metal volume 200 - 300 times and is equal to 3 - 7 μm/min depending on physical and mechanical characteristics of metal to be machined or finished.

Special investigations have proved that the Turbo-Abrasive process took place as a result of microcutting and slightly cycled fatigue destruction. Weak forces acting on a grain and also low viscosity of the fluidized bed give rise to the low temperature character of the Turbo-Abrasive machining; this fact accounts for low energy consumption. (specific power consumption is equal to 0.12 - 1.5 W/cm^3).
Deburring of fir-tree slots on turbine disk parts
Obtained mathematical models permit us to calculate the value of abrasive particle pressure on a surface and functionally depending intensity of metal removal.

**Productive Capacity of the Turbo-Abrasive Process.** Theoretical analysis and experimental investigations of Turbo-Abrasive machining processes has shown that metal removal intensity - Qm depends on a number of factors, the principal ones being: speed of a part, machining time, air discharge, median size of abrasive particles, physical and mechanical properties of a machining material, condition of initial surface, direction of surface microunevenness in relation to vector of a part velocity.

Metal removal Qm has a linearly expressed machining time dependence evidences about undamped Turbo-Abrasive machining process. Electronic microphotographs have confirmed the development of new microprotuberances on the abrasive particle surface as a result of intensive microimpact interaction. Micro-photographs insure consistency of abrasive particle cutting abilities and undamped process character.

Abrasive materials of aluminum oxide group have been used in Turbo-Abrasive machining as well as alloyed abrasive materials from the zirconium and chromium-titanium groups, with grain affect 160-800 μm, having high impact strength.

Productive capacity of Turbo-Abrasive machining depends on part velocity. The output of metal volume increases 2.8-4.0 times with increasing of velocity speed (Figure 2) from Vp = 10 m/sec up to Vp = 20 m/sec. Analysis has shown that metal removal rate decreases with further increasing of part velocity up to Vp = 30 m/sec. This is due to the formation of an air boundary which effectively prevents part surface/abrasive grain collisions. The values Qm increase 2.1 - 2.6 times with media size increasing from 100 μm up to 800 μm. Metal removal rate dependence on air stream velocity is external and proves that air flow increase leads to the layer volume expansion and as a consequence, to abrasive particle concentration decrease interacting with a surface unit, and to the output decrease, respectively. Air flow and abrasive particles are linked by parabolic dependence. While machining continuous aerodynamically well flowed surfaces, an abrasive particle will not lose its cutting ability for a long time; when machining discontinuous surfaces the stability of media particle abrasiveness decreases more rapidly as a result of intensive frontal impacts with more abruptly shaped part surfaces.

Physical and mechanical properties of the metal alloy being processed influence the quantitative results only, not changing the overall process characteristics. It is estimated that a surface roughness initial direction in relation to a vector of a part peripheral speed essentially intensifies both the metal
removal rate and metal microrelief formation.

Consumer oriented parts that have been TURBO-FINISHED

Deburring and Radius Formation. In the process of machining complex parts burrs appear on the all part edges. Mechanical deburring is one of the foremost applications for this technology. TAM processes are capable of providing cost-effective and productive solutions for demanding applications of this type.
One characteristic of Turbo-Abrasive machining is the high fringe effect (i.e., more intensive machining or finishing of edges and areas close to edges) effective deburring and rounding off sharp edges have been performed on this basis. Special investigations have been carried out concerning the above mentioned technology of deburring and rounding off edges after various cutting procedures. There were formed burrs of two types on steel disk samples: after drilling the disk openings 10 mm across; after groove milling; the groove width is 10 mm in the periphery of disk.

The initial length (bracket) of burrs after drilling reached $L_0 = 0.3 - 0.6$ mm; after milling $L_0 = 1.8 - 2.3$ mm. The burrs were removed at rotational speed $V_p$ equal to 5, 10, 20 m/sec. In this case aluminum oxide was used, with a grit value $D_g = 500; 800 \, \mu m$. Burr measures were taken by microscope with a measuring error of approximately 3%.

It is established experimentally that burrs are removed completely after being drilled, at $V_p = 10$ m/sec. If $V_p$ increases up to $20$ m/sec, time of machining decreases and is equal only to 3 min (Figure 3). Burr removal intensity increases 2–4 times in parallel with the rotational speed increase from 10 to 20 m/s in deburring process after drilling, and the grit increasing $D_g$ from 500 to 800 $\mu m$ - up to 3 times (Figure 4). This fact can be explained by the kinetic energy and impact frequency increase.

The investigations have shown that Turbo-Abrasive machining makes it possible to deburr alloys and metal materials of high plasticity as well as stainless steel parts. On brass alloys sample burrs were removed at $V_p = 20$ m/sec, but on stainless steel samples the burr removal took 4–6 min. TAM-technology allows simultaneous deburring and rounding off edges. Special investigations made it possible to define the optimum combination of different technological parameters to achieve the radii of rounding off the edges up to $R = 1.2$ mm. As far as one can see from Figure 5 any change of a part speed from $V_p = 10$ m/sec up to $V_p = 24$ m/sec increases the edge radius 1.7–2.9 times. The radius value grows 3–3.4 times with grain size growing from 250 $\mu m$ up to 800 $\mu m$. This effect of grain influence is connected with the fact that the impact energy of grain and the surface being machined is proportional to the mass of abrasive grain. The angle between the edge direction and the velocity vector of a part essentially influences on the radius of rounding off edges. The edge radius increases 4.1 times on the average and equals to $1.0 - 1.2$ mm with the angle change from $\alpha = 0$ up to $\alpha = 30$ (Figure 5). Therefore it is possible to operate both the deburring and the rounding off edges processes by changing the technological machining regimes.

On basis of these experiments and investigations the technology of mechanized deburring has been developed concerning such parts as gear wheels, gas-turbine disks, parts after "cold" pressing, etc.
Surface Finish. In Turbo-Abrasive machining high-frequency micro-impact interaction of abrasive grains produces a surface micro-relief and outer metal structure that improves part operational and functional properties. TAM-technology can achieve surface roughness values $Ra$ equal to $0.2 - 0.4 \ \mu$m for different steels and alloys, at the initial roughness $Ra$ equal to $3 - 5 \ \mu$m. This technology permits to obtain homogeneous micro-relief formation also. After Turbo-Abrasive machining the relation $R_{max}/Ra$ equals $6 - 8\$, while after grinding the relation $R_{max}/Ra$ is equal $10 - 12$. Turbo-Abrasive process is a low temperature "cool" one. After Turbo-Abrasive machining residual compression stresses with $MPa = 300 - 600$ are formed on a surface layer of metal in the depth of $20 - 40 \ \mu$m (Figure 6); micro-roughness shapes are characterized by large radii of rounding off $R_{pr} = 200 - 400 \ \mu$m as well as small slope of the sides $\theta = 0.8 - 1.6$. The above mentioned character of residual stresses in combination with absence of single deep scratches concentrating stress results in the significant increase of the components fatigue strength.

In the case of alternating bending of steel plates in fatigue strength testing (vibrations amplitude is $0.52 \ \text{mm}$, load stress equals $90 \ \text{MPa}$) the destruction of specimens machined by Turbo-Abrasive method takes place after $(3 - 3.75) \times 10^4$ cycles and the destruction of ground plates starts after $(1.1 - 1.5) \times 10^4$ cycles.

The results obtained after gas-turbine engines samples tests are of great interest. Disks manufactured of titanium alloys and high temperature (on the Ni base) alloys have been machined by both Turbo-Abrasive technology and previously used one (grinding with the help of hand tool and finish polishing). After Turbo-Abrasive machining the average Figure of fatigue limit $\sigma_1$ amounts to $330 \pm 20 \ \text{MPa}$, while after semi-mechanical treatment $\sigma_1$ is equal to $250 \pm 43 \ \text{MPa}$. Thus TAM-technology increases the value $\sigma_1$ $1.3$ times, at the same time decreasing the value of dispersion $\sigma_1$ more than two times. Gas-turbine disk tests have been carried out on a special stand in a condition equivalent the disk load when the engine started working. The following parameters have been specified: the number of cycles before scratches appeared; (length up to $0.3 \ \text{mm}$) $N_{sc}$; the number of cycles before the disk destruction $N_{des}$. It has been found out that the disks after Turbo-Abrasive treatment have the values: $N_{sc} = 7300 \pm 700$, $N_{des} = 13090 \pm 450$ cycles while after semi-mechanical treatment they have the values: $N_{sc} = 2600 \pm 700$, $N_{des} = 5685 \pm 335$ cycles. Thus the Turbo-Abrasive machining increases the cycling life of disks $2.2 - 2.5$ times providing the increase of engine resource. Contact rigidity being an operating characteristic is indicative of reliability and sealing of detail joints while they are assembling. The testing has shown that the contact rigidity of steel parts surface after turbo-abrasive machining increases by $50 - $
Complex parts shapes effectively deburred with dry media only.
60% in comparison with the grinding surface.

It will be noted that there are other useful operating-surface characteristics after Turbo-Abrasive machining, for example: strong bond with various coatings, (electrodeposited, plasma coatings, etc.) and also reliable retention of lubricant film. Thus it has been found out at testing stand that oil consumption for piston rings after Turbo-Abrasive machining decreases by 2.5 - 4.0% in relation to fuel consumption. The above mentioned figures have testified to high effectiveness of TAM - technology as a new abrasive machining method.

Equipment and Fields of Application. This semiautomatic equipment aimed at machining of parts from 50 - 1200 mm has been developed and used in the machine building industry in the former Soviet Union.

There are different types of Turbo-Abrasive equipment designed for multiple and mass production. The Turbo-Abrasive process is performed in automatic cycle; the operator's duty is only to load and unload the work pieces. The productive capacity of the equipment is 60 - 80 pcs/h, while machining other pieces the productive capacity amounts to 120 - 180 pcs/h and even more.

The process of Turbo-Abrasive machining proves to be highly effective in solving the following technological problems:

- Deburring after various cutting operations as well as after stamping;
- Rounding off sharp edges, the radius of rounding off being controlled;
- Decreasing surface roughness to \( E_a = 0.2 - 0.4 \ \mu m \) for components made of structural and stainless steel, high-temperature, non-ferrous and titanium alloys;
- Surface preparation before coating;
- Descaling after thermal treatment, carbon deposit removal, etc.

While solving the above mentioned tasks Turbo-Abrasive machining makes it possible to mechanize and automate labor-intensive manual operations, to increase productivity 3 - 10 times, and to improve and stabilize the quality of machined components.

The Turbo-Abrasive method is used in finishing working disks of turbines, compressors, and gas-turbine engines manufactured of high-temperature and titanium alloys for the aircraft and power industries. Testing has shown that the fatigue strength limit of disks increases by 26 - 38%, when TAM is used as a mechanical finishing process. High efficiency is a distinctive feature of the Turbo-Abrasive machining of gear-wheels in the process of deburring and rounding off the edges after gear-tooth cutting. This technology is also used in the automotive industry for rotor
Electron microscope photomicrograph of surface after turbo-abrasive machining (X400)

a - traces of single grains (Vp=15 m/sec; Dg=320 µm)
b - surface after 10 minutes machining

Single microunevenesses traces of abrasive grains impacts (Vp=15 m/sec; Dg=630 µm)
machining of mechanisms for turbo-charging (Figure 7). The new method has been also used for finishing treatment of piston rings. Testing has shown that achieved piston ring surface microrelief contributes to better lubricant film retention as well as decreasing lubricant consumption. TAM technology can be successfully applied in machining diamond cut-off wheels and circular saws. It has also been used on agricultural machinery such as shearer comb-cutters for sheep shearing, processed after tooth cutting, 186 comb-cutters being processed simultaneously, with a process time of 10 minutes (e.i. 3 - 5 seconds for each comb-cutter).

All of the above mentioned applications illustrate a wide range of possibilities for Turbo-Abrasive machining, which can be applicable where other technologies can not be used or are less effective. This new method can provide manufacturers the capacity to finish complex parts cost effectively, and develop surface finish characteristics that are more refined and more functionally useful than the manual or conventional methods being currently utilized.
REFERENCES:


Lsc and Nsc dependences of part rotational speed $V_p$

(Lsc - a scratch length, $\mu$m; Nsc - a number of scratches per mm$^2$)
Metal removal dependence $Q_m$ of a part rotational speed $V_p$

1 - brass; 2 - steel; 3 - aluminum
FIGURE 3

Part speed $V_p$ and grain size $D_g$ influences on burr removal intensity at drilling:

1 - $V_p = 5$ m/sec; $D_g = 800$ µm
2 - $V_p = 10$ m/sec; $D_g = 800$ µm
3 - $V_p = 20$ m/sec; $D_g = 800$ µm
4 - $V_p = 10$ m/sec; $D_g = 500$ µm
5 - $V_p = 20$ m/sec; $D_g = 500$ µm
6 - $V_p = 5$ m/sec; $D_g = 500$ µm
Part speed $V_p$ and grain size $D_g$ influences on burr removal intensity at milling

1, 3 - $V_p=20$ m/sec, $D_g=800$ µm
2, 4 - $V_p=20$ m/sec, $D_g=500$ µm
Radius rounding off (edges) and dependence of particle speed $V_p$ and abrasive grain $D_g$

1 - $D_g=250 \, \mu m$; 2 - $D_g=500 \, \mu m$; 3 - $D_g=800 \, \mu m$
Radius rounding off (edges) Red dependence of part speed $V_p$ with the various angle change $\alpha$

$1 - \alpha=0^\circ$, $2 - \alpha=15^\circ$, $3 - \alpha=30^\circ$
Residual stresses $\sigma$ after turbo-abrasive machining of alloys on Ni, Cr, Ti base

1 - Ni; 2 - Cr; 3 - Ti