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EFFECTIVE UTILIZATION OF IN-PROCESS ENERGY SOURCE FOR SURFACE HARDENING AND QUALITY IMPROVEMENT IN GRINDING

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Abstract Grinding is a versatile finishing process used for producing component with close tolerances, geometrical accuracies and smooth surface finish. Compared to other machining processes such as turning, milling, etc., in grinding the specific energy developed during machining is very high. At a critical level of specific grinding energy the temperature rise(2) experienced by the workpiece may be such that thermal damage is induced. Heat damage induced by the grinding process is well documented and may be categorised by temper colours which are at least unsightly and probably indicative of more serious damage including thermal cracks, tempered zone, etc.,(10) which can lead to catastrophic failure of critical machine parts which shorten the life of products subject to cyclic loading. In this present work, new heat treatment process called "*Grind Hardening*" and a mathematical modelling are introduced and it deals with how the in-process energy in grinding can be effectively utilized to improve the surface hardness and surface integrity and also to prevent damages . Experimental study has also been carried out in grinding AISI 4140 and AISI 52100 steels with Alumina wheel and the results are discussed.

Keywords: Metal, Surface hardening, Surface integrity and Partition ratio.

INTRODUCTION

In recent years high strength and high temperature alloys evolved are used for structural and various other applications. These newer high performance materials are inherently "more difficult to machine" and also necessitate the need for higher dimensional and geometrical accuracy. Grinding is one of the most familiar and common abrasive machining processes used for finishing operations.

In the past many scientists investigated the dissipation of heat in grinding and resulting influence on the surface integrity of the workpiece. Depending on the grinding conditions the heat flux mainly takes part via the workpiece and leads to a large thermal loading in the surface. This thermal load is superimposed by mechanical load causing a high temperature in the surface. This thermo mechanical load is able to cause some undesired alterations in the surface layer like cracks, tempered zones or white etching areas (WEA). If the material in the surface layer is heated above the characteristic temperature during grinding, diffusion and phase transformation takes place. While Shaw and Vyas (10) gave an impressive theoretical description of metallurgical damages in ground surfaces. Under abusive grinding condition the formation of heat affected zone (HAZ) was observed which damages the ground surface.(4). A thermally damaged component may therefore incur a significant cost to the manufacturer in failing a quality standard.

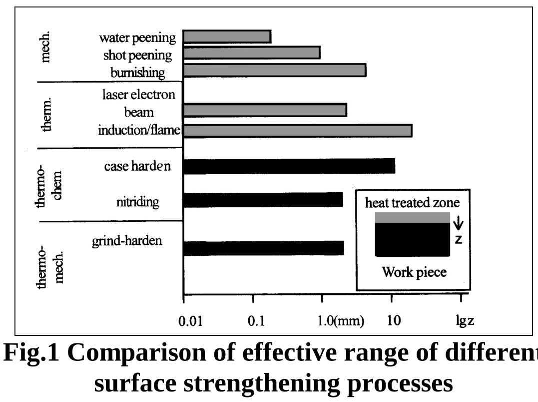

Fig.1 Comparison of effective range of different surface strengthening processes

The main aim of the most investigations was the prediction of undesired alterations in order to avoid thermal damages when grinding hardened steels (6). In any case, the generated heat quantities in grinding are considered as a restricting factor. By concluding todays experience in heat treatment and grinding, three important limitations can be identified.

(i) There are many heat treatment processes for surface hardening, but they are very difficult to integrate into the production line.
(ii) They cannot be done perfectly as in the case of irregular objects and contour shaped objects.
(iii) Subsequent to heat treatment, structural parts are subjected to grinding.

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The above said problems caused the authors to investigate, how this process generated heat energy can be effectively utilized for quality improvement in cylindrical grinding.

WORKPIECE MATERIAL

The reason for the adjustable properties of steel is the temperature dependent appearance of "α" and "γ" mixed crystal with different solvent abilities for carbon. The hardening mechanism is based on phase transformation of austenite into martensite starting at a defined critical cooling rate and being characterized by shearing of austenite lattice (Face Centered Cube) to the martensite lattice (tetragonal distorted).

A survey paper specifically on grinding was presented by Konig [5] in which he says "It is impossible to describe the behaviour of the workpiece during grinding using a parameter dependent on a work material", he makes the following two fundamental observations for practice:

(i) **"Martensite"**, which is a structure of uniform hardness is much more easily grindable than work material in which the hardness has been produced by means of carbides. Not only the carbide content but also the size and distribution of hard material inclusion exert considerable influence on the grinding ratio. Structures of uniform hardness cause mainly abrasive wheel wear, while striking of a grain against extremely hard carbides causes grain splitting.

(ii) The grinding ratio can be raised considerably by adding sulphur. This sulphur inclusion promotes chip breaking and produces a protective layer between grid and chip, which lubricates and prevents chemical reaction between grain and the work material. The hardening mechanism mainly depends on the carbon and other alloying elements content of the material.

In this present work **AISI 4140** and **AISI 52100** steels have been selected as work materials.

INFLUENCE OF PROCESS PARAMETERS

In case of cylindrical grinding there are many parameters that can be varied namely

(i) depth of cut (ii) feed speed and (iii) number of passes.

The heat generated is proportional to the depth of cut at contact zone, because higher depths of cut result in longer heat treatment duration. Increasing depths of cut lead to higher quantities of energy entering into the workpiece (7).

Increasing feed speed is generally connected with increasing process forces, which also was found for grind hardening process. The main two effects of feed speed was described by Brockhoff that is

(i) At very low feed speed the travelling energy is high, due to lower cutting power, the extend of hardened layer is reduced.

(ii) At very high feed speed, the cutting power increases, but due to the decreased contact time and lower travelling energy the extend of the hardened layer is once again reduced.

Thus a moderate or medium feed speed is always preferable to produce maximum hardness in the surface.

EXPERIMENTATION

Investigations were carried out experimentally with varying depths of cut, feed and number of passes. For the attainment of grind hardening, a standard alumina grinding wheel was employed and rough grinding conditions were selected. This means that a high specific material removal rate was necessary to induce martensitic phase transformation.

In this experiment the number of passes were varied according to the rough and finish grinding. The grinding conditions are given in Table 1.

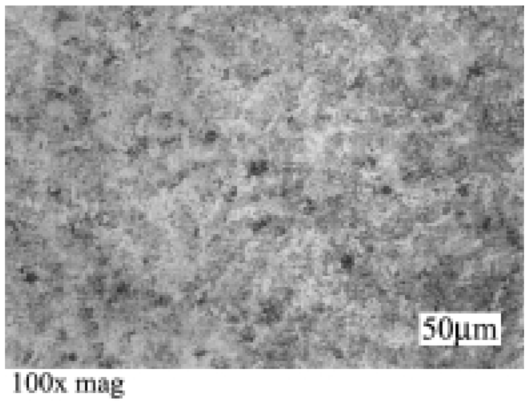

Fig.2 Microstructure of ground specimen (AISI 52100)

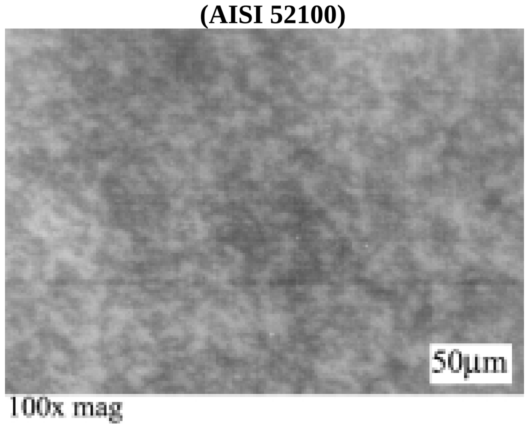

Fig.3 Microstructure of ground specimen (AISI 4140)

From the microstructures, (shown in Figs. 2 & 3) it is evident that the bulk of chip produced during machining has etched darkly but white etching bands (The carbide atoms are almost fully segregated all along the ferritic matrix, i.e., a fine martensitic structure is generated.) are present. This etching response suggests that temperature of about 800^{0}C have been reached in the bulk of chip and that temperature of 1000^{O}C or more have been reached in the white etching bands. (3) Thus, the temperature at the workpiece surface could have an important influence on metal removal at large wheel depth of cut. However, heating and cooling of the surface would occur rapidly and this may have the influence of producing phase changes in the surface. The theoritcal model developed in this present work was also gives the same temperature that developed at the contact area. The following graphs (shown in Figs. 4 & 7) shows the course hardness of the ground material at various depths beneath the surface.

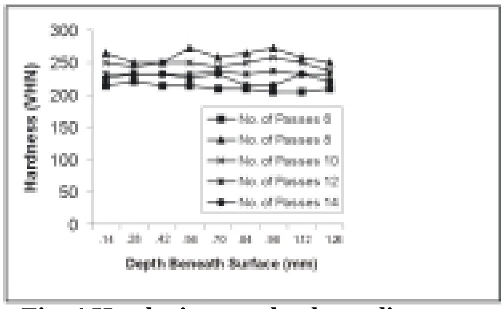

Fig. 4 Hardening results depending on number of passes (AISI 4140)

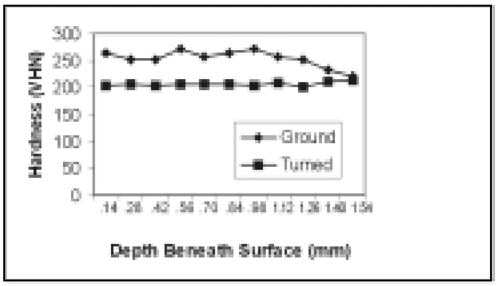

Fig. 5 Comparison of hardness of turned and ground specimen (AISI 4140)

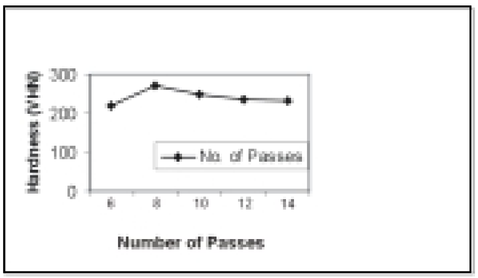

Fig. 6 Influence of number of passes (AISI 4140)

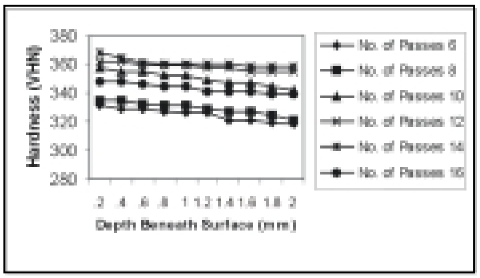

Fig.7 Hardening results depending on number of passes (AISI 52100)

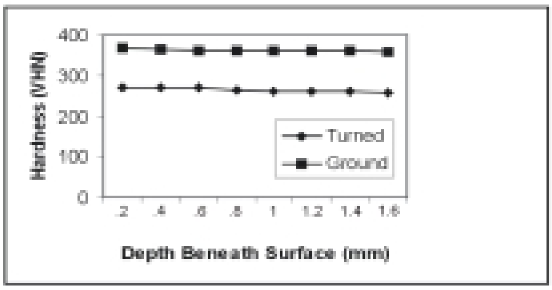

Fig. 8 Comparison of hardness of turned and ground specimen (AISI 52100)

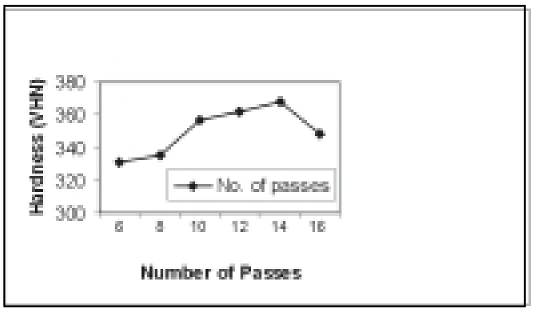

Fig. 9 Influence of number of passes (AISI 52100)

Table - 1 : Grinding Conditions

Process	: Cylindrical Grinding
Grinding Wheel	: Alumina A46L5V
Materials	: AISI 52100 & AISI 4140
Cutting Speed	: 30 m/s
Coolant	: Emulsion

The higher hardness obtained during this grind hardening effect when comparing ground specimen with turned specimen is shown in Figs. 5 & 8. The experiments were carried out with the application of coolant, however the coolant doesnot have much impact in the grind hardening effect.

The higher depth of cut and increased number of passes (showh in Figs.6 & 8), the area and the time for heat transfer is increased due to increased (to certain depth of cut only) energy.

CONTROL OF SURFACE INTEGRITY

Surface integrity is defined as the inherent or enhanced condition of a surface produced in a machining or other surface generating operation (12). It was found in many cases, the nature of the surface layer has strong influence on the mechanical properties of the material. This association is more pronounced in some materials and under certain machining operations.

Typical surface integrity problems include

(i) Grinding burns on high strength steel landing gear components.

(ii) Untempered martensite in drilled holes.

(iii) Effect of cutting fluid on the stress corrosion properties of titanium.

(iv) Grinding cracks in root section of cast nickel base gas turbine buckets.

(v) Distortion of thin components and

(vi) Residual stress induced in machining and its effect on distortion, fatigue and stress corrosion.

On structural applications, the nature of declivity troughs of the surface is the most important. While on bearing applications, the nature of the crests of the surface is more significant, keeping in mind this above said application, the surface roughness of the ground specimen was also measured and the results were plotted. (shown in Figs.10&11) The results are at acceptable level.

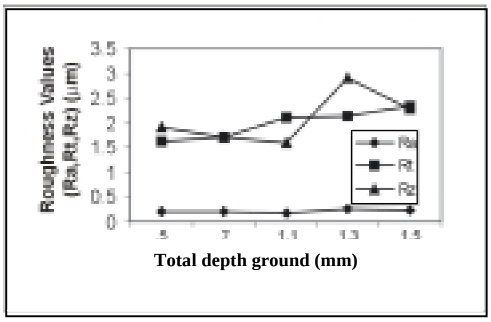

Fig. 10 Surface roughness values of a ground specimen (AISI 4140)

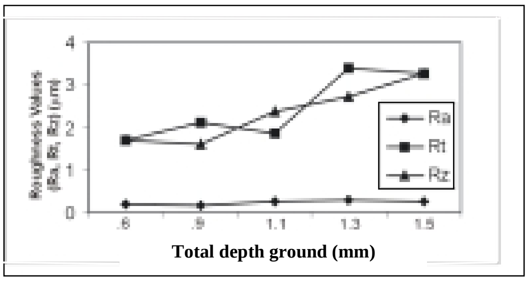

Fig.11 Surface roughness values of a ground specimen (AISI 52100)

TEMPERATURE MODELLING

Usually the validity of thermal approach is substantiated by means of evaluating the various thermal properties using various correlation theories and experimental results.

In this case the grind hardening effect is being quantified by means of heat entering into the workpiece.

Terminology Involved

Partition Ratio (*R*): The partition ratio is the proportion of the heat entering the workpiece to the total heat (9).

$$R = Q_w / Q_t$$

where

Q_w - Amount of heat entering the workpiece (J)

Q_t - Total heat produced (J)

For a square law distribution the partition ratio is given by

$$R = 0.83 \cdot b \cdot \sqrt{(k\rho c)w} \cdot \sqrt{V_w}\,\sqrt{l_e} \cdot \theta_m / Q_t$$

where

b - Grinding width (m)

$\sqrt{(\kappa\rho c)w}$ - Thermal contact coefficient for workpiece ($Jm^{-2}S^{-0.5}K^{-1}$)

V_w - Work Speed (m/sec)

l_e - Grain Contact length (m)

θ_m - Background temp (^{0}C)

Q_t - Total Heat Produced (J)

Justification for using square law distribution is based on the assumption that the heat distribution to be uniform along the contact area and the flow is radially inward to the work (9).

THEORETICAL MODEL

Theoretical models are required to predict the partition ratio and workpiece temperature. First is grain contact zone model proposed by Rowe and Black (8) by considering the partitioning of energy over the whole grinding contact.

$$1/R' = 1 + \{V_s/V_w \cdot [(k\rho c)_s / (k\rho c)_w]\}^{1/2}$$

where

V_s - Speed of the grinding wheel (m/s)

V_w - Speed of the workpiece (m/s)

$\sqrt{(\kappa\rho c)_s}$ - Wheel bulk thermal co-efficient ($J\ m^{-2}\ s^{-0.5}\ K^{-1}$)

From the tool magazine it was found that for an alumina wheel, the bulk thermal coefficient

$$\sqrt{(\kappa\rho c)_s} \Rightarrow 2\ kJ\ m^{-2}\ s^{-0.5}\ K^{-1}$$

The bulk thermal co-efficient for each workpiece material is found by using their physical properties

$\sqrt{(k\rho c)_w} \Rightarrow$ AISI 52100 $\Rightarrow$ 10.5 $kJ\ m^{-2}\ s^{-0.5}\ K^{-1}$

$\sqrt{(k\rho c)_w} \Rightarrow$ AISI 4140 $\Rightarrow$ 12.8 $kJ\ m^{-2}\ s^{-0.5}\ K^{-1}$

Using the Rowe's Contact zone model (8) the partition ratio for various workpiece materials were found.

For AISI 52100

Work speed (V_w) $\Rightarrow$1.099 m/sec
Wheel speed (V_s) $\Rightarrow$30 m/sec

$$1/R' = 1 + \{ (V_s/V_w) . [(k\rho c)_s / (k\rho c)_w]\}^{1/2}$$

$1/R'=1+[(30/1.099)^{1/2}(0.2/10.5)] = 1.0995$

On solving
$R' = 0.90948 \cong 0.91$
$\mathbf{R' = 0.91}$

For AISI 4140

Similarly, on solving
$R' = 0.9246 \cong 0.925$

$$R' = 0.925$$

If we consider the allowance for the energy convected away by the chips (e_{cc}) and coolant (e_{cf}), then the predicted partition ratio is reduced, i.e.

$$R = R' [1- \{ (e_{cc} + e_{cf}) / e_c\}]$$

where
e_c - Specific chip energy (J/mm^3)
According to Howes and Neailey, typical value of e_{cc} is 6 J/mm^3 and e_{cf} tends to be very small where fluid boiling occurs [$e_{cf} = 0$] (10).
Thus considering the allowance the original partition ratio can be given by

$$R = R' [1- (6/e_c)]$$

The effect of chip energy becomes increasingly significant at lower specific energies.
According to Rowe and Black the specific energy of the chip is assumed to be

$$e_c = 30 \text{ J /mm}^3$$

Thus the partition ratios for the work piece material were found as

$$R = R' . \{ 1 - (6/30)\} = R' . [0.8]$$

therefore

$$R = R' [0.8]$$

Workpiece	Partition Ratio (R)
(i) AISI 52100	0.728 @ 0.73
(ii) AISI 4140	0.74

Using the grain contact model developed by Rowe and Black, the solution for partitioning of heat between the wheel and the workpiece is

$$R_{ws} = 1/ \{1 + (k_{ge}/\sqrt{r_o}.V_s) . [1 / \sqrt{(k\rho c)_w}]\}$$

where
kge-Thermal conductivity of the grinding wheel(Wm^{-1}K^{-1})
for Alumina wheel $\Rightarrow$ *kge* = 35Wm^{-1}K^{-1}
r_o - Radial depth of cut (µm)

For AISI 52100

$$R_{ws} = 1/ \{1 + (k_{ge}/\sqrt{r_o}.V_s) . [1 / \sqrt{(k\rho c)_w}]\}$$

$R = R_{ws} = 0.73 = 1/ \{ 1 + (35/r_o.30) . 1 + (10.5 \times 10^3)\}$
On solving

$$r_o = 2.71 \times 10^{-6} = 2.71\mu m$$

Optimal grain contact length (l_e)

$$l_e = \sqrt{r_o}\, d_e$$

It is known that

$$d_e= [d_s.d_w/ (d_s + d_w)]$$

Where
d_e - Equivalent diameter (m)
d_s - Dia of wheel (m)
d_w - Dia of workpiece (m)

$d_e = [(0.035)(0.35)/(0.035)+(0.35)]$
on solving

$$d_e = 0.0318 \text{ m}$$

therefore

$$l_e = \sqrt{(2.71 \text{ x } 10\text{-}6) (0.0318)} = 0.2935 \times 10^{-3} \text{ m} = 0.29\text{mm}$$

Grain contact time (t)

$$t = l_e/V_s$$

$t = 0.29 \times 10^{-3} / 30 = 9.72 \times 10^{-6}$ µsec
on solving

$$t = 9.66 \text{ µsec}$$

Calibration of the total heat entering into the workpiece

From the square law distribution

$$R = Q_w/Q_t = 0.83 \; b \sqrt{(k\rho c)_w} . \sqrt{V_w} . \sqrt{l_e} . \theta_m / Q_t$$

Therefore

$$Q_w = 0.83 \; b \sqrt{(k\rho c)_w} . \sqrt{V_w} . \sqrt{l_e} . \theta_m$$

For AISI 52100

The total heat entering into the workpiece
$Q_w = 0.83 [0.06] [10.5\text{x}10^3] [1.099]^{½} [0.2935\text{x}10^{-3}]^{½} (32)$

on solving

$$Q_w = 300J$$

It is known that $\mathbf{Q = kA \Delta t/dx}$ $\{dx = 1\text{(unit length)}\}$
where
k - Thermal conductivity.(Wm^{-1}K^{-1})$\Rightarrow$ 43.3 Wm^{-1} K^{-1}
A = Area (m^2)
= 6.597 x 10^{-3} m^2

$$\Delta T = Q/ kA$$

$\Delta T = 300 / (6.597 \text{ X } 10^{-3}) (43.3)$
on solving

$$\Delta T = 1050 \,^0\text{C}$$

$$T_1 = 1083 \,^0\text{C}$$

For AISI 4140

$$R_{ws} = 1/ \{1 + (k_{ge}/\sqrt{r_o}.V_s) . [1 / \sqrt{(k\rho c)_w}]\}$$

$R = R_{ws} = 0.74 = 1/ \{1 + (35/\sqrt{r_o}.30) . 1 / (12.8 \times 10^3)\}$

on solving

$$r_o = 2.0188 \times 10^{-6} = 2.0\ \mu m$$

Optimal grain contact length (l_e)

$$l_e = \sqrt{r_o . d_e}$$

$$l_e = \sqrt{(2.0 \times 10^{-6})}\ (0.0318) = 0.25 \times 10^{-3}\ m$$
$$= 0.25mm$$

Grain contact time (t)

$$t = l_e/Vs$$
$$= 0.25 \times 10^{-3} / 30 = 8.43\ \mu sec$$

For AISI 4140

The total heat entering into the workpiece

$Q_w = 0.83\ (0.06)(12.8 \times 10^3)\ (1.099)^{½}\ [0.25 \times 10^{-3}]^{½}\ (32)$

on solving

$$Q_w = 338\ J$$

It is known that $Q = kA\ \Delta T/d_x\ (d_x=1)$

where

$$k = 53.6\ Wm^{-1}K^{-1} \text{ and } A = 6.599 \times 10^{-3} m^2$$

on solving

$$\Delta T = 955\ ^0C$$
$$T_1 = 987\ ^0C$$

This temperature developed at the contact area is the real cause for the phase transformation, i.e., austenite into martensite.

CONCLUSION

Experimental investigation shows that the heat generated in cylindrical grinding could be effectively utilized as a new heat treatment process. Surface cracks were not found in the grind hardened component which are normally subjected to compressive residual stress (1) and the same was also found by using magnetic induction test. Parts that are used under normal loading conditions can be easily grind hardened. The grind hardened parts are characterized by fine grained martensitic layers up to a depth of 1 mm (HPD=1mm) (shown in Fig.1). There is a considerable increase in hardness up to a depth of cut of 1mm after that the hardness decreases (shown in Figs.4 & 7).

The theoretical temperature modelling were also developed by using grain contact model by Rowe and Black (9) to find out the temperature at the interface between the cutting grain and the workpiece which also gives the best agreement with the suggestions given by Doyle and Dean (3). Actually the temperature developed at the contact area is the main source for the phase transformation i.e., austenite to martensite. Summing up it has to be noticed that the adoption of this new surface strengthening method includes great economical benefits due to its increased integration level and it is also a technological alternative to the other surface hardening processes. This leads to shorter production sequences and reduced throughout time as well as decreased cost. Possible industrial applications for surface hardening by the grinding lie in the production of running faces for rotary shaft seals, camshaft, lateral faces of the bearings, guide ways and many other functional surfaces which are frequently ground (shown in Fig.12). Nevertheless, for all new applications a detailed technological and economical analysis is required taking the individual shop floor conditions into account. It is to be concluded that the quest to find a way to reduce the cost involved in the manufacturing has attained its culmination. It is hoped that this new heat treatment process called *Grind Hardening* would go a long way in the achievement of economic manufacturing and in a broader perspective for an Integrated Manufacturing System.

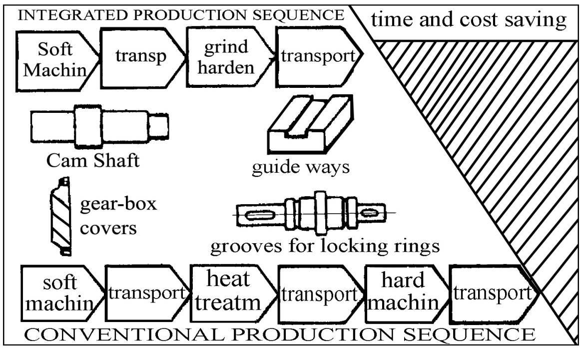

Fig.12 Industrial parts for grind hardening

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