Roller Finishing of Cylindrical Components

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ABSTRACT

Roller finishing is a recently developed surface finishing technique based on the non cutting metal cold forming process. High specific rolling forces are generated in the contact zone between the rolling tools and the work piece resulting in plastic deformation of the surface roughness. The magnitude of the required rolling forces depend greatly upon the hardness of the material to be roller finished. As a result of the surface rolling, a diameter reduction is experienced which averages the magnitude of a full peak to valley depth. Surface finish values of better than 5 RMS are obtainable in production from turned components of more than 125 RMS. Further distinct advantages of roller finishing are increase of hardness and bearing area contact, geometry improvement and manufacturing cost reduction in producing a high quality surface finish. Simplicity of tooling and machines make the roller finishing process more attractive for any manufacturing industry.

I. INTRODUCTION

A. Definition of the Process

Roller finishing is basically a process through which the surface roughness of premachined cylindrical components is cold worked or cold formed through the use of precision rolling tools and high specific rolling forces. This definition of the roller finishing process indicates a very close relationship with cold forming. The name "roller finishing", however, pronounces the relationship with the finishing process. To determine clearly under what manufacturing technique roller finishing has to be categorized, it is necessary to define the cold forming process. Cold forming today utilizes sectional changes from 10% to 80%. This means that cold forming produces predominantly a macro geometric form change on the component. Roller finishing, on the contrary, employs the cold forming process only for improving micro geometric form accuracy. The degree of sectional change is minimal and not truly compatible with the definition for cold forming. The roller finishing process must, therefore, be considered a non coating finishing technique utilizing cold forming only in the outer material layers. Despite the low degree of metal flow taking place in the roller finishing process, the well known advantages for cold forming metals as strength increase, size accuracy, surface quality and low manufacturing cost are also utilized.
B. Development of Roller Finishing

Already (50) fifty years ago, roller finishing was used by the industry. Predominantly the Railroads employed this process under the name of burnishing for finishing the sleeve bearing seats on railroad axles. This process is still employed today where the sleeve bearings have not been replaced by anti-friction bearings. Roller finishing was and is also known by the industry under different names as for example roller polishing, pressure polishing or bearingizing, all of which describe the same basic process under use of slightly varying techniques. Even though these surface cold forming processes were known and used much earlier than most of the surface finishing techniques based on the abrasive principle, roller finishing has just recently and predominantly in Europe been recognized as an efficient and competitive surface finishing process.

The more extensive use of the abrasive processes in the past is probably reasoned by the fact that these manufacturing methods were subjected very early to scientific research. Thus resulting in a better understanding of these processes, leading to the development of proper tooling, machines and machining techniques.

The intensive scientific research of the roller finishing process dates back only (15) to (20) years (1,2,3,4). As a result high productive tools and machines were developed. Within its scope of suitability, roller finishing will reduce manufacturing cost, increase reliability, and improve quality.

Three basic processes are developed for rolling cylindrical components:

1. Roller Finishing
2. Size Rolling
3. Deep Rolling

Related processes as stress relief rolling or form rolling are also commonly used terms. These, however, describe only the predominantly desired effects inherently typical for the three basic rolling processes. (Figure #1)

II. COLD FORMING OF THE SURFACE MICRO STRUCTURE

The relationship between rolling force, material strength, tooling and work piece diameters, surface roughness and rolling time were not clearly understood when roller finishing was initially used. The obtained results remained quite often unacceptable. Flaking of the surface was mostly experienced on low quality steels either during the rolling
process or after subjecting the rolled component to its operational functions. The explanation for this surface failure was falsely interpreted as resulting from bending and shearing of the surface peaks remaining from the preparatory turning or grinding operation. Surface roughness traces showing an uneven amplification between roughness width and roughness height supported this opinion. Comparing the true relationship between roughness height and width will clearly show the impossibility of this theory. (Figure #2)

A. Metal Flow

Roller finishing requires generally a preparatory machining operation either in the form of turning or grinding. Surfaces, as for example, resulting from a swedging operation as typical on gun barrels have also been very successfully roller finished. The cold forming which takes place when rolling the surface roughness is best explained in the following manner:

The work rollers forced against the surface peaks will generate in the plastification zone a steadily increasing compressive stress. At a certain stress level, plastic flow of the material will occur in the direction of the least resistance, towards the surface valleys. This, in turn, will lift the valleys up to the level of the work roller. (Figure #3)

The magnitude of the plastic flow is depending upon the rolling forces used. In certain applications it is desirable to select a rolling force which does not permit the surface valley to close up entirely. The typical characteristics of such a surface are lubrication capability, combined with a high bearing area contact. A volume reduction on the part piece does not take place, however, the diameter will reduce as a function of the surface roughness before and after rolling.

B. Cold Forming Zones

The roller finishing theory defines three zones in the contact area between the work roller and the work piece. (Figure #4)

On the leading edge of the work roller is the contact or LEAD ZONE followed by the PLASTIFICATION ZONE and on the trailing part of the work roller, the FINISHING ZONE. For through feed operations the work roller axis is slightly inclined relative to the work piece axis, so that a drop form contact is generated. The length of the drop form is mainly determined by the work piece hardness, the roughness or waviness of the surface or the desired feed rate. Most
commonly drop form lengths vary from 1/4" to 1-1/8". For
plunge rolling operations the work roller axis must be
maintained parallel to the work piece axis in order to
generate a line contact. This results in an elimination of
the finishing zone, which in turn could require a finer
surface finish preparation compared with the feed rolling
process. The setting of the line contact over the roller or
part length must consider the machine deflection, present
under the required rolling forces.

III. ROLLING FORCE AND ROLLING STRESS

The rolling forces required for plasticizing the
surface roughness of a component depend upon the strength of
the work piece material, the length of the contact form, and
the size of the contacting work piece and work roller
diameters. The rolling force is calculated according to the
following equation:

\[ F = \text{Rolling Force} = S_{RF} \times L \times D \text{ (Lbs.)} \]

\[ S_{RF} = \text{Specific Rolling Force (PSI)} \]

This factor expresses the required
specific rolling force in relation
to the material strength. (Figure #5)

\[ L = \text{Length of drop form between the}
work piece and the work roller. (In.) \]

\[ D = \text{Relative Diameter (In.)} \]

The relative diameter \( D \) is depending
upon the work roller diameter \( D_1 \) and
the work piece diameter \( D_2 \). They are
related according to the following
equation:

\[
\frac{1}{D} = \frac{1}{D_1} + \frac{1}{D_2} \quad \text{For External Roller Finishing}
\]

\[
\frac{1}{D} = \frac{1}{D_1} - \frac{1}{D_2} \quad \text{For Internal Roller Finishing}
\]

A very simple and practical means to determine the
contact length is to make an imprint between the work roller
and the work piece by using onion skin paper between both
components. The contact length is clearly visible and can be
measured.

Under known conditions of the tool diameter and the
contact length, the required rolling forces can be graphically
shown in relation to the work piece diameter and the material
strength. (Figure #6)

The highest shear stress and plastification according to the stress distribution theory from Hertz and Foeppl during rolling is not on but rather under the surface of the work piece. Subsurface shear failures caused when rolling with excessive rolling pressure will, therefore, result in flaking of the surface.

The well known characteristic of steel to work harden under plastic deformation explains the fact that roller finished components show an increase in surface hardness. The greatest hardness increase is measured below the surface on account of the stress distribution. Actual hardness tests confirm this condition. (Figure #7)

The surface hardness increase as a result of cold working can be measured only to a relatively shallow penetration depth. Conventional hardness testing methods as the Rockwell test or the Brinell test cannot be employed for testing the hardness increase, because the testing media would break through the hardness scale under the preloads. Micro hardness testing techniques have to be employed as for example the Knoop test working with preloads of 50 or 100 gramm. The hardness increase can range from 2 to 8 Rockwell "C" points whereby the lower value is experienced for components already high in hardness to begin with.

IV. TOOLING ARRANGEMENTS

The relationship between the mass of the work piece and the mass of the tooling will determine generally whether the rotating motion is generated by the work piece or the tooling. If the moment of inertia for a work piece is high in comparison with the tooling, the component will be held between centers. Rotational motion in this case is transmitted from the work piece to the tools. The latter arrangement is mostly used when roller finishing large components with a two-roll attachment. Bending of the work piece or deflections on the rolling machine are eliminated due to the opposed work roller arrangement. Roller finishing with a two-roll attachment can be performed as a plunge operation or as a feed operation with parallel or inclined work roller axis respectively. The feed rate has to be generated by the machine since the work piece is held between centers. (Figures #8 and #9)

If the moment of inertia of the work piece is small, the centerless rolling principle will be employed. The rotational motion is generated by the drive roller which, in turn, under rolling pressure, provides rotational motion to the work piece and work rollers. The tooling for the centerless rolling principle does permit plunge or feed rolling operations. The necessary roller axis inclination is adjusted
on the tool head. The feed rates are generated by skewing the axis of the roller head towards the axis of the work piece. (Figures #10 and #11)

The work rollers must be designed to the smallest possible size in order to reduce the required rolling force to a minimum. Optimum conditions are offered by the multiple work roller attachments. Standard roller heads for centerless roller finishing machines represent a design compromise with small floating work rollers backed up by properly supported back up rollers. Considerations as bearing life for the back up rollers or the (3) point contact geometry between the work rollers and the part are the reasons that a roller head can only be designed for a certain diameter range.

V. ROLLER FINISHING INFLUENCE FACTORS

A. Number of Overrollings

The number of overrollings to which a particular surface element is subjected during the roller finishing process can be an important factor with regard to surface failure especially for materials with a low ductility. The number of work rollers used, the length of the drop form and the feed rate per work piece revolution determine the number of overrollings. As a general rule, a minimum of three overrollings per surface element are desirable, however, very satisfactory surface finishing results were obtained with only one overrolling. The maximum number of overrollings for steel is not critical especially with increasing hardness. Cast iron or screw machine materials, however, require to control the number of overrollings on account of the sensitivity to subsurface shear failures. These materials are further sensitive to changes in rolling directions. The micro section (Figures #12 and #13) show the grain structure, true peak to valley relationship of a turned sample before and after rolling and the directional alignment of the grain structure as a result of the cold forming.

B. Rolling Speed

Extensive tests which were performed to determine the best suited rolling speed for roller finishing in relation to various materials showed that speed is of no consequence with regard to surface finish. Equally good surface qualities were experienced with either low or high roller finishing speeds. Also the tool wear or diameter reduction are not affected by changes in rolling speed.

Further considerations, as for example the required floor to floor time, the part piece acceleration, dynamic behavior of the work piece and heat in the tooling or bearings limit the rolling speed to a practical value. Best results
were achieved with rolling speeds of approximately 200 ft/min for diameters up to 1½" and 400 ft/min for diameters over 1½". Very small diameters of 1/16" to 3/16" should be roller finished below 100 ft/min. The reason being that the part piece revolution could be excessively high.

The rolling tools must always contact the work prior to start of the rotation and acceleration to rolling speed. Excessive slippage will cause wiping of the work piece material. This condition might not be readily apparent and could cause an out of round condition which possibly is only recognizable through roundness measurements.

C. Lubrication During Roller Finishing

Lubrication during the rolling process does not effect the surface quality. With regard to the feed rate, a lubrication oil between the work piece and the tooling can even be undesirable because of slippage which will take place, resulting in a feed rate reduction. Various reasons, however, make a light spindle oil desirable during the rolling process. A continuous stream of filtered and recirculated lubrication oil will flush dirt and metal particles out of the reach of the rolling tools. This can be quite desirable when rolling certain materials, for example stainless steel. Stainless has the typical characteristic of flaking minute surface particles which is caused by the work hardening capability of the material. Surface finish qualities are not affected by this phenomenon. A light spindle oil is often also used to lubricate the anti-friction bearings holding the work rollers.

VI. SURFACE FINISH AND SIZE ACCURACY

Roller finishing has the objective to produce a fine surface finish through rolling of the surface roughness. This cold working process, if properly employed, will produce surface finishes between 1 to 5 RMS starting from a turned surface of 125 to 150 RMS finish. The feed rates which can be obtained are compatible with feed rates produced by the centerless grinding process. Maximum feeds of .040" per work piece revolution have been measured for the centerless principle. Work pieces made of a material with low suitability for cold working or of high hardness must be prepared to a relatively fine surface finish.

Roller finishing will reduce the diameter of the components depending upon the surface roughness prior to rolling and the surface finish after rolling. The diameter reduction will average approximately four times the changed RMS value in millionths of an inch. (Figure #14) Provided that the surface roughness prior to rolling and the rolling force are kept within a permissible variation limit, this diameter reduction will be constant. The most accurate way of
determining the diameter of reduction would be rolling tests after the proper machine setup or finishing effect have been obtained. Work pieces which require very close dimensional tolerances must be machined to a size considering the diameter reduction for shafts or diameter increase for bores. Even though a finish grinding operation to obtain the required dimensional accuracy might become necessary, roller finishing still offers considerable advantages beyond surface quality.

Another means to obtain high dimensional accuracy is to premachine the work piece to a relatively coarse surface finish of approximately 150 to 200 RMS. Roller finishing with a multiple work roller attachment will provide the desired dimensional accuracy. Dimensional deviations resulting from the preliminary machining operation will, however, lead to a varying surface finish and bearing area contact.

The surface quality of the component is not only determined through the surface roughness prior to rolling and the hardness of the material, but also dependent upon the form accuracy. Figure #15 shows the rolling results of inaccurately machined surfaces. It should also be mentioned here that the use of excessive roller finishing forces could cause undesirable changes in geometry of the component for example piece elongation, tapers on shaft ends, metal flow into grooves or small cross holes.

VII. STRESS BALANCE AND MACRO GEOMETRIC FORM CHANGES

The plastic deformation taking place during the roller finishing process, as already mentioned above, cause a hardness increase and compressive stress layer in the surface of the work piece. The compressive stresses are symmetrical to the work piece axis and should not result in any macro geometry changes of the component. Past experience, however, has shown that a bending of long components can occur. This condition was initially interpreted as an insufficiency of the roller finishing process. More detailed investigations have shown that a cylindrical component will only bend if an unequal stress pattern exists in the component prior to rolling. Preliminary operations as cold forming, heat treating or machining could cause this condition. The unbalanced stresses will be relieved during the rolling process and result in bending of the part.

Of similar nature can be a certain type of surface flaking, sometimes experienced in a line pattern parallel to the part axis. This type of failure would point out that the preliminary machining operation has not undercut an already existing surface crack. Failures of this nature are mostly caused by an overlapping during the cold drawing operation. Grinding will not make these minute cracks visible which can only be detected by magnafluxing or similar
techniques. The hidden cracks, however, cause excessive noise level and bearing wear during operation of the component. Normally connected with these failures is also a bending of the shaft since the stress balance has been disturbed.

Roller finishing does, as shown above, discover manufacturing insufficiencies which in the past have probably never been properly recognized.

VIII. ADVANTAGES AND LIMITATIONS OF ROLLER FINISHING

The advantages provided by the roller finishing process are many. This new cold forming technique results primarily, as the name already indicates, in the desired surface finish. Under proper selection of the rolling forces, best suited surface finishes for improved wear resistance can easily be obtained. The degree of finish depends upon the application. The bearing diameter for a seal for example, should not be roller finished below a surface value of approximately 15 RMS. The stem diameter of an engine valve, on the contrary, could be roller finished to a surface value of 8 RMS provided that the stationary valve guide is manufactured with a properly selected surface roughness capable of lubrication oil retention.

Roller finishing on the centerless principle will, as the result of the tooling contact, improve the roundness geometry of cylindrical components. This pertains especially to the typical insufficiencies experienced with centerless grinding as chatter or lobing. Badly chattered work pieces will not be made perfect through rolling. The rate of roundness improvement, however, is increasing with a greater degree of chatter or out of round condition. Surface waviness, as often experienced for tracer turned components, will greatly be improved provided that the drop form length is longer than the waviness width.

The surface finish together with the roundness geometry improvement will result quite favorably in noise level reduction predominantly for armature shafts running in sinter-metal sleeve bearings providing only a microscopically thin oil film with no cushioning effect.

The surface hardness increase, as already mentioned, is in favor of an increased wear resistance. This effect, together with the obtainable surface area contact of over 95%, will permit to eliminate in many cases the required surface hardening process. The roller finished surface character reduces greatly notch sensitivity which, together with the compressive stress layer, results in an increased fatigue life of the component.

Direct cost savings are provided through roller finishing by eliminating and replacing conventional surface finish-
ing processes such as grinding, polishing, lapping or honing. The manufacturing cost savings to produce a 4 RMS surface finish in relation to various accuracies is well demonstrated in Figure #16. Another substantial area of direct cost savings provides the possibility to eliminate heat treating operations, for example induction hardening. Indirect cost savings are achieved by reduced tool costs, possible material changes to lower grades, or savings on grinding wheel costs. Further cost savings are possible by relaxing the required quality control.

The limit of the roller finishing process is the hardness of the component. Roller finishing can still be effectively performed slightly above the general limits for machinability, 40 to 45 Rockwell "C". Surface hardness has no influence on the speed or cycle time. A component of high hardness level can, therefore, be roller finished in the same time as a low hardness work piece. Processes have been developed to bypass the hardness specification, for example on piston rods. The induction hardening operation will take place after roller finishing. The resultant surface oxidation is removed through a chemical washing process prior to chrome plating. Many applications, as for example shock absorber rods, will permit to reduce the hardness level into a range of approximately 40 Rockwell "C" which can be handled by roller finishing and will still provide a hard enough surface to avoid surface scratching during the assembly or caused by material handling.

IX. ROLLER FINISHING EQUIPMENT AND APPLICATIONS

The diameter of the component to be roller finished determines generally the equipment or rolling procedure used for roller finishing.

Small bearing length and cylinder bores are predominantly roller finished by multiple work roller attachments. These attachments are mostly mounted onto an engine or turret lathe, but also used as standard tooling on special machines. (Figure #17) The diameter adjustment is relatively limited and the setting remains constant during the rolling operation. Changes in diameter size will reflect onto the surface finish. The work rollers are symmetrically arranged and retained in a manner which allows them to produce a drop form contact with the work piece. As already mentioned, these fixed diameter attachments have the disadvantage of requiring a good size control prior to roller finishing; sometimes even beyond the drawing requirements. Especially well suited are these attachments for internal roller finishing operations. Their use for external work is limited and restricted to short bearing extensions. Special work roller finishing attachments for tapers, chamfers, spheres and fillets are also available on the same design principle.

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General purpose semi-automatic roller finishing machines and single purpose fully-automatic machines are available up to a maximum work piece diameter of 4". (Figures #18 and #19) These machines work on the centerless principle. The tooling can be adjusted to any desired drop form or line contact. Feed rates are infinitely variable within the machine capability. The required rolling forces are generated by means of hydraulic pressure. Tooling and machine are designed in a manner to provide optimum flexibility with regard to manual or automatic operation, adaptation of loading devices or transfer lines. The diameter range of a tool head can be utilized without adjustments, which make the finishing effect independent of any diameter changes. Machine setup and tool changes can be performed at a minimum time to conform to high production requirements.

The two roll and single roll attachments are, in their design, compatible. (Figure #20) The single roll attachment, however, should only be used on diameter sizes which warrant that no deflection of the work piece or the machine takes place when rolling forces are applied.

<table>
<thead>
<tr>
<th>WORKPIECE DIAMETER (In.)</th>
<th>ROLLING EQUIPMENT</th>
<th>TYPICAL APPLICATIONS</th>
<th>ROLLING FORCE (Lbs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/16 to 4</td>
<td>Roller finishing machines and Internal Rolling Attachments.</td>
<td>Valve stems, shock absorber rods, bolts, armature shafts, dental drills, pump plungers, seal diameters, rocker arm shafts, drive shafts, piston rods, speedometer shafts and textile shafts.</td>
<td>200 - 10 000</td>
</tr>
<tr>
<td>4 to 25</td>
<td>(2) Roller Attachments and Internal Rolling Attachments (16&quot; dia. only)</td>
<td>Piston rods, tie rods, turbine shafts, rolls for paper and plastic industry.</td>
<td>200 - 18 000</td>
</tr>
<tr>
<td>Above 25</td>
<td>Single Roll Attachment</td>
<td>Rolls and Roll Bearings</td>
<td>1500 - 4 000</td>
</tr>
</tbody>
</table>

The above chart shows the diameter ranges and the general limitations of the rolling equipment. It further conveys a
picture of the mostly used applications and the rolling pressure requirements for the respective diameter ranges.

X. SUMMARY

Roller finishing of cylindrical components as discussed above offers many advantages. The theory of the process has been thoroughly developed as well as the design of tooling and machines. A meaningful and successful application of this new surface finishing technique does require to understand the relationship between the specific rolling force, material strength, contact length between tooling and work piece, number of overrollings, and preliminary surface preparations. If properly applied, roller finishing and its results will satisfy the demands brought forward by today's progressive industry in providing manufacturing cost reductions, increasing performance reliability, and improving the component quality. The roller finishing process of cylindrical components will in the future, undoubtedly, gain a wide acceptance because of the steadily increasing trend towards metal cold forming.

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Schematic Tooling Arrangement for the Three Basic Rolling Processes

Figure #1 - Page #2, line #39.

False and True Roughness Height and Width Relationship

Figure #2 - Page #3, Line #8.

Stress Pattern and Metal Flow of the Surface Roughness

Figure #3 - Page #3, Line #25.

Figure #4 - Page #3, Line #39.
Figure 5, page 4, line 23

Figure 6, page 5, line 1

Figure 7, page 5, line 14

Figure 8, page 5, line 40
Figure #14, sheet 7, line 45

Figure 15, sheet 8, line 19

Figure 16, sheet 10, line 4