Simulation Studies on the Contact Behavior of Elastic-Abrasive Spheres and Feasibility of Its Magneto-Mechanical Deployment for Internal Finishing

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Abstract

Contact behavior of elastic abrasive spheres during its interaction with a target surface under normal loading is simulated using ANSYS, and compared with the contact nature of a standard Al_2O_3 grit. The presence of elastomeric medium was clearly exhibiting an effective reduction in the depth of penetration of grain into the surface, attributed to the reduction of effective elastic modulus and deformation of spheres by the absorption of energy. With a significantly lower depth of cut and under the action of a controlled cutting velocity, such balls are capable of generating fine finish without altering the surface form. Conceiving this idea, a deployable type tool with self centering magnetic pads to hold magnetic elastic abrasive spheres has been introduced in this paper. The design, development and operation of such a tool is illustrated using experiments, with positive finishing results to prove its capability.

Keywords: Finishing, Elastic abrasives, Magnetic, Contact, Deployable, Self Centering

1. INTRODUCTION

Finishing is one of the most important phases in the fabrication cycle of a number of aerospace/mechanical components. A series of advanced abrasive finishing methods are being developed to make the finishing operation simpler, faster and precise at micro-scale as well as nano-scale levels, such as abrasive flow finishing, magnetic abrasive finishing, magneto rheological finishing etc. [1]. Though such methods could achieve the micro/nano-finish, requirement of costly abrasive medium, tooling requirements to suit the work piece geometry etc., brings several limitations on its way to commercial applications [1,2]. Due to this, theoretical and experimental studies on such abrasive processes have gained central attraction among the manufacturing researchers in the recent past. Conventional abrasive grits in its loose and bonded form, indented directly on a surface, can generate sub-surface damages due to considerably higher depth of penetration. Elasto-abrasive finishing is one of the advanced abrasive finishing techniques developed to address the aforementioned issue. Elastic-abrasive spheres are abrasive embedded elastomeric beads that can be made in micro-to-meso size range. Presence of elastomeric medium makes the spheres capable of deforming in conformity to the work surface and effectively brings down the contact forces. Due to this, a delicate refinement of surface profile is expected without any severe sub-surface damage and form variation. Various experimental results reported by Sooraj and Radhakrishnan [3-6] could illustrate the effectiveness of elasto-abrasive spheres in its magnetic as well as no-magnetic configurations. Magnetic type elastic abrasive spheres are produced by embedding ferromagnetic powders in controlled quantity to the elastomeric beads, in addition to abrasive powders [6]. Recent publications related to this topic could demonstrate the feasibility of using magneto-elastic abrasives for fine finishing of internal bores [7]. Considering its industrial relevance, the present paper addresses a computational and experimental study related to this finishing strategy.

The paper mainly addresses the study of the contact behavior of elastic abrasive spheres under normal loading condition, simulating the action of radial finishing forces. Interaction between elasto-abrasives and work surface is modeled and simulated in ANSYS to understand their deformation behavior. Static structural analysis and Explicit Dynamics in ANSYS were used for the analysis, considering various configurations of elasto-abrasive spheres. In tune with this fundamental contact behavior of elasto-abrasive spheres, a self centering type-magnetic- elasto-abrasive tool has also been proposed for finishing internal bores.

2. MATERIALS, METHODOLOGY AND EXPERIMENTAL DETAILS

2.1 Contact analysis of elasto-abrasive sphere on surface

To simulate the contact of elasto-abrasive sphere on work surface, a sphere of 3.5 mm diameter and a solid work piece of cuboid shape with length x width x thickness of 12 x 4x 4 mm were modeled in the design modeler of ANSYS. To make an effective meshing and to facilitate faster computation, a face split was made on the work piece in the form of a square of 2.5 mm, centered at the contact point of sphere and work piece. A counter face split was made on the sphere by projecting the former face split. The lower surface of the work piece was fixed during the interaction, simulating the clamping of work piece. All the edges of the aforementioned face splits were edge sized with 50 divisions and the region was mapped with face meshing for capturing the interaction at more precise level, as shown in Figure 1. The contact of elastic abrasive spheres on various work materials were simulated for the conditions described in Table 1.

2.2 Feasibility of deployable elasto-abrasive tool for internal finishing

Conceiving the advantages of using elastic abrasive spheres, a special tool capable of deploying and self centering has been proposed in this work. The tool mainly consists of deployable jaw pads, *similar to a self centering chuck,* on which permanent

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ISBN: 978-93-80689-28-9

magnets are attached. The magnets are designed to hold magnetic-elasto abrasive spheres, which will come into contact with the inner surface of a tubular specimen (target to be finished). As the spheres are loaded against the work surface through the deployment, the tool can be rotated at a predefined speed followed by its translation in Z direction. The combined effect of radial loading (depth of cut) and reciprocating cutting velocity of hard abrasive spheres will facilitate the material removal from the surface. However the presence of elastomeric medium will allow a very small quantity of material removal without affecting the circularity, cylindricity and run-out of the target surface.

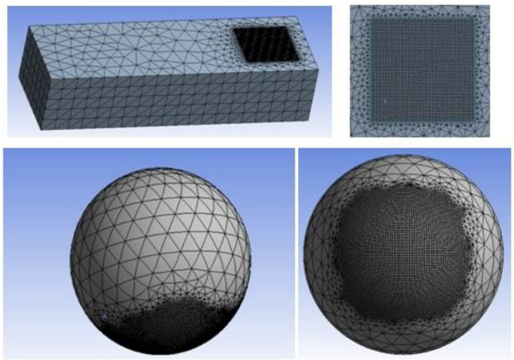

Fig.1. Meshing scheme for spheres and work surface

Table 1: Combinations of work material and spheres for simulation

Work Material	*Hardened Steel*	
Configuration of Spheres (average diameter of sphere = 3.5 mm)	Type 1	*Elasto abrasive spheres with polymer-abrasive –magnetic powder ratio 30: 50: 20*
	Type 2	*Elasto abrasive spheres with polymer-abrasive- magnetic powder ratio 40: 40: 20*
	Type 3	*Elasto abrasive spheres with polymer-abrasive-magnetic powder ratio 60: 20: 20*
	Type 4	*Standard Aluminum Oxide*
Normal Force	10 N *(acting on the Sphere in contact with work surface)*	

2.2.1 Configuration of the proposed finishing tool

The proposed tool consists of a blind tubular housing (part 1 in Figure 2) with three radial holes made at a height of 7.5 mm from its bottom. The holes are located 120^0 apart, through which three specially made threaded jaws (part 4) are mounted as shown in Figure 2. Outer ends of the jaws are fixed with square pads to accommodate the permanent magnets (Part 3). The jaws are designed to move outward, analogous to a three jaw self centering chuck. To facilitate this movement, a face threaded stepped cylinder (part 2) is assembled over part 1, moving the jaws through the engagement of threads in part 2 and part 4. While the shaft in part 2 is rotated, the engagement of threads will drive the jaws uniformly outwards, making a self centred movement.

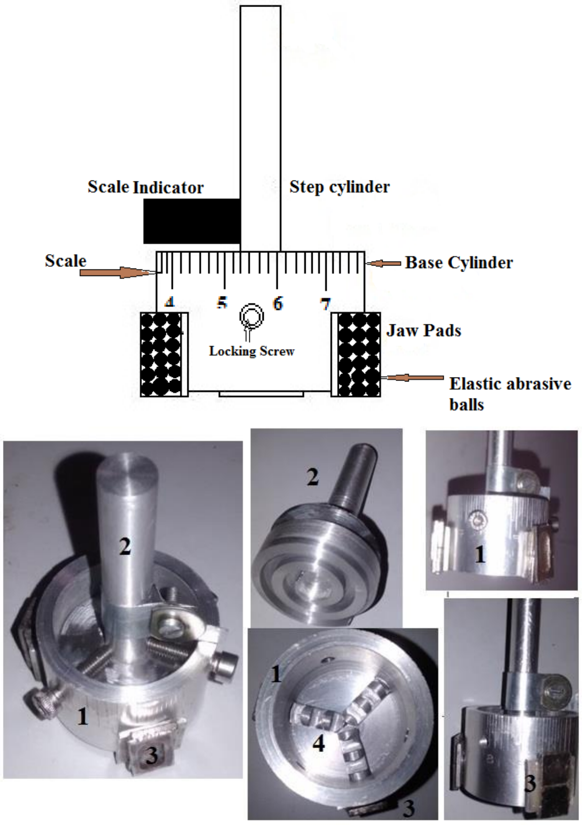

Fig.2. Design and Configuration of the deployable tool

2.2.2 Experimental setup for finishing

During the finishing experiments, the assembled tool was clamped on the spindle of a CNC milling machine, on the cylindrical shaft of part No. 2. The tool can be locating easily inside the tubular workpiece to be finished (loacted in the machine bed), before starting the experiments. As the shaft is roated, the stepped cylinder with face threading (part No.2) will rotate and thus the threaded jaws engaged with the same will get deployed to touch the worksurface. Since the jaw movements are syncronized through the threadings, the self centering of the tool will be achieved easily. Magnetic elatsic abrasive spheres of average diamter 3.5 mm were attached to the magnets on the jaw pads, as shown in Figure 3. The elastic abrasive spheres between the magnetic jaw pads and the worksurface are free to move (roll, slip or abrade), similar to the condition of three-body abrasion. The major process variables that could affect the processes are the *Roatational velocity of tool; Size of the spheres ;Size, Shape and type of the abrasives embedded on the spheres*; *Magnetic charcteristics of the ball*; *Normal force on the work surafce by the abrasive grit (due to the radial deployment)*; *Type of work surface* ; *Initial roughnes of target surface* etc.

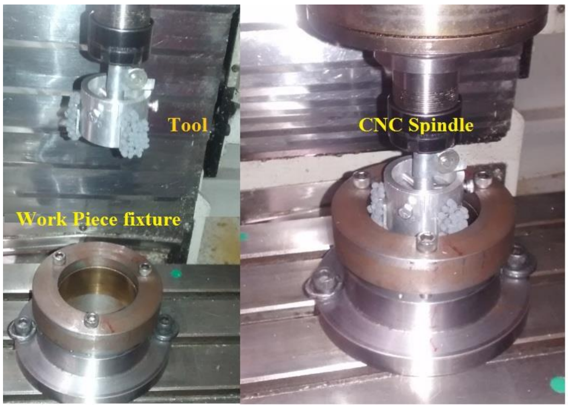

Fig.3. Details of experimental setup

3 RESULTS AND DISCUSSIONS

3.1 Contact behavior of elasto-abrasive ball under abrasion

The stress field and deformation on the work piece caused by the contact of magnetic elastic abrasive sphere of average diameter 3.5 mm, in comparison with a similar size aluminium oxide sphere as well as rubber sphere are shown in Figure 4 and 5. Results were clearly indicating the effect of elastomeric medium. It is understood that the presence of elastomeric medium will reduce the equivalent elastic modulus at the contact interface and significantly reduces the normal contact force [8-10]. Due to the reduction in normal force, the depth of penetration (deformation) of the sphere at the contact interface will also get reduced. In an actual finishing situation, the depth of penetration corresponds to the depth of cut and an effective reduction in the volume of material removal will be achieved by the usage of elastic abrasive spheres. In comparison with normal abrasive grits of similar size, elastic abrasives can be used for fine refinement of surface texture without severely affecting the surface form. The maximum contact stress and deformation observed against typical compositions of elastic abrasives, in comparison with standard abrasive grit, are indicated in Table 2.

Table 2. Magnitudes of contact stress and deformation

Type of sphere	Maximum Stress on the work piece (N/m^2)	Maximum deformation on work piece (μm)
Al2O3	**3×10^9**	**4.0**
Elasto-abrasive ball 30:50:20	**8×10^8**	**0.9**
Elasto-abrasive ball 50:30: 20	**8.4×10^8**	**0.6**
Elasto-abrasive ball 60:20:20	**4.6×10^7**	**0.04**

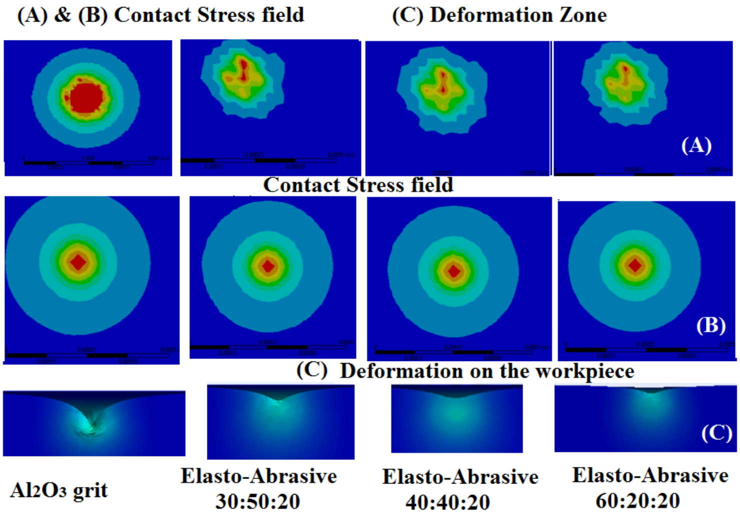

Fig. 4. Simulation results at various sphere configurations

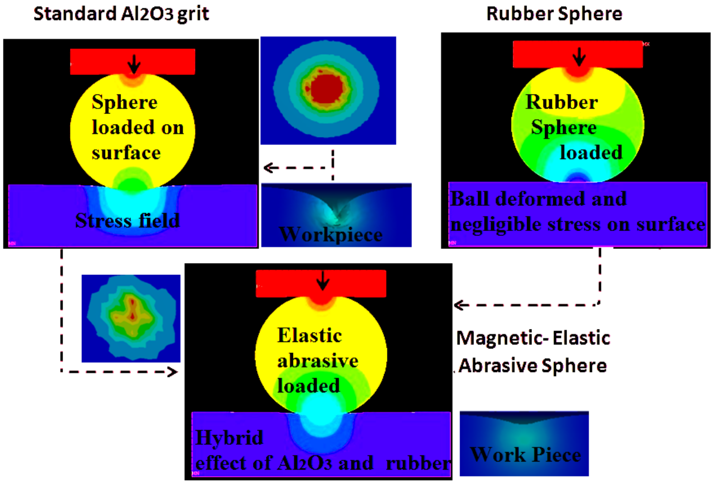

Fig. 5. Deformation characteristics of elastic abrasive spheres in comparison with rubber and Al_2O_3

3.2 Finishing Results: Refinement of roughness profile

Table 3. Roughness before and after finishing measured at 0.25 mm cut off (Rotational speed of tool = 600 rpm and reciprocating feed =0.1 mm/ rev)

Parameter	Before Finishing	After Finishing
Ra (μm)	1.0302	0.2627
Rp (μm)	2.1570	0.7459
Rt (μm)	10.4925	3.2988
Rz (μm)	6.6267	1.5668

The two dimensional roughness parameter before and after finishing, using the proposed magnetic-elastic abrasive tool are shown in Table 3. The results were clearly validating the hypothesis derived out of simulation studies. The contact of abrasives in presence of elastomeric medium was proven to be effective for fine refinement of surface texture, without affecting the surface form. The proposed tool design is found to be capable of self centering and deploy itself conveniently to finish geometrically symmetric internal surfaces. The cylindricity of the bore and its dimensions were not affected during the process, validating the influence of elastomeric action. The feeding of elastic abrasive spheres into the finishing zone was very convenient using the proposed tool and cleaning after finishing was also made simpler. The sphere connected through magnetic pads were free to move in the finishing zone, bringing out the advantages of both bonded as well as loose abrasive finishing.

4. CONCLUSIONS

The paper simulated the contact of magnetic elastic abrasive spheres over steel surfaces using ANSYS and the results were compared with a normal abrasive (Al_2O_3) grit of similar size. The results were clearly validating the hypothesis of controlled depth of penetration due to the presence of elastomeric medium included in the elastic abrasives. Considering the practical advantages of such elastic abrasive spheres, a special tool was designed and developed, with the capability of self centering and deployability. The proposed tool can be used for the finishing of geometrically symmetric internal surfaces using magnetic elastic abrasive spheres. Experiments were performed using the proposed tool, in a CNC milling machine, by adopting very simple and cost effective fixtures. The preliminary results were strongly validating the hypothesis and strongly supporting the influence of elastomeric medium observed during simulations. The reduction in average roughness from 1.03 µm to 0.26µm, with a similar trend in peak to valley roughness, was a motivating lead to further scope of studies.

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