High-Quality High-Productivity Manufacturing of Variable Valve Timing Parts by Green Machining

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In recent years, variable valve timing (VVT) systems have been increasingly used for vehicle engines. The most common VVT is hydraulic systems because they require fewer parts and production costs are lower. However, the rising concern about the environment and demand for improved fuel efficiency have made VVT systems more complicated. We have developed a green machining technique that enables the one-chuck processing of a large number of complicated holes and lateral grooves and established a simple machining line for smart production. For quality assurance, compacts can be traced by 2D codes applied after in-line green machining.

Keywords: Variable valve timing system, green machining, 2D code

1. Introduction

Variable valve timing (VVT)*[1] systems, which are increasing being used for automotive engines, boost fuel economy and reduce exhaust emissions by making the usually fixed opening/closing timing of the intake/exhaust valves controllable. VVT systems are roughly classified into hydraulic and electric systems; at present, hydraulic VVT systems are used more widely since they have fewer parts and are therefore cheaper to manufacture. A hydraulic VVT system is mainly composed of a sprocket, housing, and rotor. Since the shapes of these parts are suitable for forming by sintering process, sintered VVT parts have increasingly been used since the 2000s. Meanwhile, in response to growing public concern about environmental protection and fuel efficiency, the functions and performance of VVT systems are being improved. Accordingly, the oil passages formed in the systems for hydraulically controlling the component parts are becoming more complex (Photo 1). An example is a VVT system with a built-in oil control valve (OCV). The OCV, which is constructed by additionally cutting oil grooves in the inner diameter surface of the VVT rotor, controls the flow of pressurized oil to minimize the number of necessary parts. Since it is usually impossible to form horizontal holes or inner diameter grooves with molds in a powder metallurgy process, these holes and grooves are machined after the parts are sintered. However, deburring sintered parts after machining increases the manufacturing cost and may deteriorate their quality.

To solve these problems, we developed a line for producing VVT parts that can achieve high-productivity, high-quality machining of the new VVT rotors shown in Fig. 1. We introduced green machining technology*[2] into the new production line under the concepts of 1) drilling many complexly-arranged holes and cutting inner diameter grooves in green compacts by optimizing the machining conditions and cutting tool geometry, 2) establishing a touchless, stockless, in-line machining of green compacts by synchronizing compacting and green machining, and 3) ensuring the traceability of each product by printing a 2D code*[3] on each green compact.

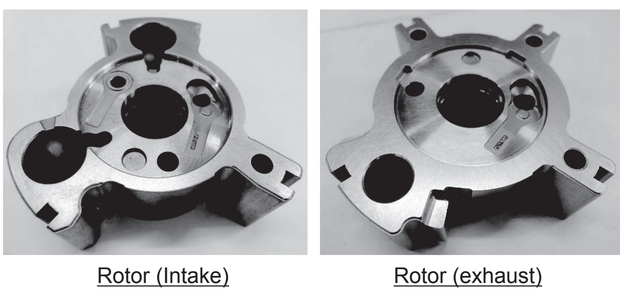


Photo 1. External Appearance of VVT Rotor

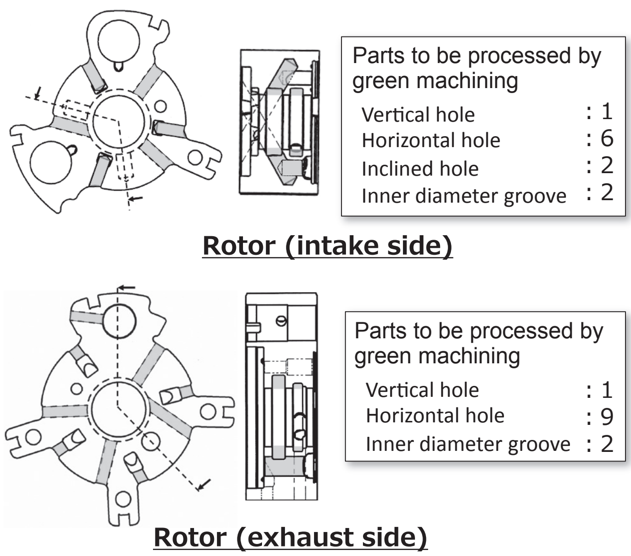


Fig. 1. Products and Their Parts to be Processed by Green Machining

2. Development of Green Machining Technology

The usual process flow for making sintered parts is shown in Fig. 2. In the compacting process, raw powder composed primarily of iron is poured into a mold and compressed to 500 to 700 MPa on a compacting press to make a "green compact." The green compact is merely a packed mass of metal powder. The constituent particles are not yet metallurgically bonded and the shape of the mass is maintained by only the mechanical entanglement force of each particle. The green compact is subsequently conveyed to a sintering process and burnt at a temperature of approximately 1100°C to 1200°C. In this process, the powder particles are metallurgically bonded together to become a sintered body or part. After sintering, the part can be processed in the same manner as ingot steel.

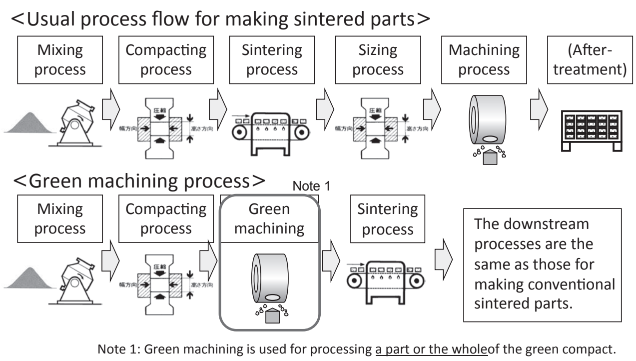


Fig. 2. Conventional Parts Sintering Process Flow and Green Machining Process Flow

We developed a green machining technology useful for shaping parts in the state of green compacts in which the powder particles are not yet metallurgically bonded together, as shown in Fig. 3. Compared with conventional sintered part machining, green machining can process the parts at lower shearing stress.

The primary features of green machining are that it 1) ensures high productivity, 2) reduces cutting tool wear, 3) allows the use of relatively compact processing equipment due to low cutting resistance, and 4) does not produce burrs since it does not plastically deform metal particles. Some

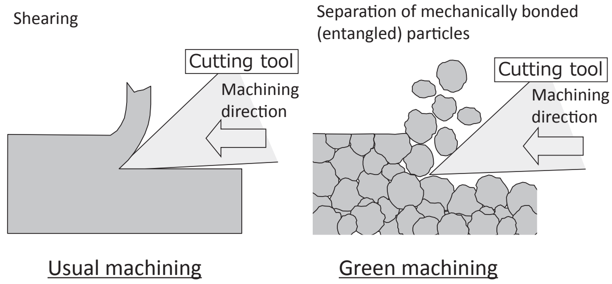


Fig. 3. Comparison between Usual Machining and Green Machining

application examples of green machining include drilling of intersecting holes[2] by utilizing feature 4). Deburring drilled intersecting holes is difficult.

On the other hand, the major problems regarding green machining are: 1) the workpiece may chip or suffer cracks since it is a ductile green compact; 2) the parts of the workpiece that can be machined are limited due to low dimensional accuracy and large surface roughness (such parts must be machined after sintering the workpiece); and 3) dust-prevention measures and special-purpose workpiece handling systems are required.

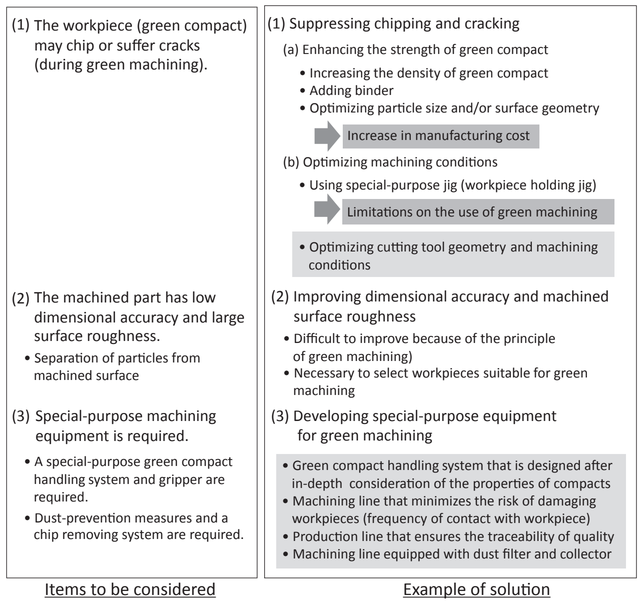


Fig. 4. Problems Regarding Green Machining and Example of Solution

A possible measure for protecting the workpiece from chipping and cracks (problem 1) is to enhance its strength by increasing the density of the green compact or adding a binder. However, this measure requires higher compacting pressure, which will shorten the mold's service life and increase the raw material cost. Some examples of green machining that prevented the workpieces from chipping by holding them at non-machining parts have been reported.[1],[3],[5] However, the major drawback of this method is that it narrows the range of workpiece geometries that can be processed by green machining.

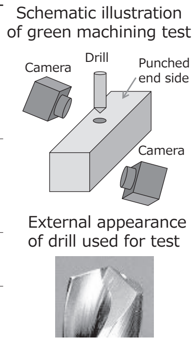
To solve these problems, we developed a VVT parts green machining line that can: 1) prevent green compacts from chipping by optimizing the cutting tool geometry and machining conditions, 2) minimize the risk of deteriorating the quality of machined workpieces by protecting them from chipping and cracking while being handled, and 3) make the quality of products traceable.

2-1 Development of cutting tool for green machining

At the initial stage of developing a cutting tool suitable for green machining, we investigated the chipping mechanism of green compacts. To do this, a green compact having a green density of 6.9 g/cm^3 was prepared as shown in Table 1. A hole was bored in this green compact with a 4 mm-diameter drill. In this procedure, chipping of the hole circumferential edges on both the drill entrance and exit sides was recorded by a high-speed camera.

Table 1. Green Machining Test Conditions

Test specimen	Test specimen dimensions : 10 × 10 × 50 mm Material composition : Fe-2.0Cu-0.8C–0.8%Lub (EBS) Green density : 6.90 g/cm^3
Cutting tool	Drill diameter : 4 mm Point angle : 120° Material : High-speed steel * General-purpose metalworking drill
Machining conditions	Drill revolution speed : 6000 rpm Vf : 1600 mm/min
Description of investigation	Drilling Φ4 through-hole to investigate chipping of circumferential edges on both drill entrance and exit sides



The chipping investigation results are shown in Fig. 5. On the drill entrance side, the circumferential edge of the hole chipped extensively when the outer corner of the drill contacted the workpiece and the chipped edge remained even after the hole was completely bored. We considered that reducing the drill point angle would effectively prevent green compacts from chipping at the circumferential edges of drilled holes on the entrance side. Reducing the point angle will reduce the stock allowance at the drilled hole edge per revolution of the drill, thereby reducing cutting resistance.

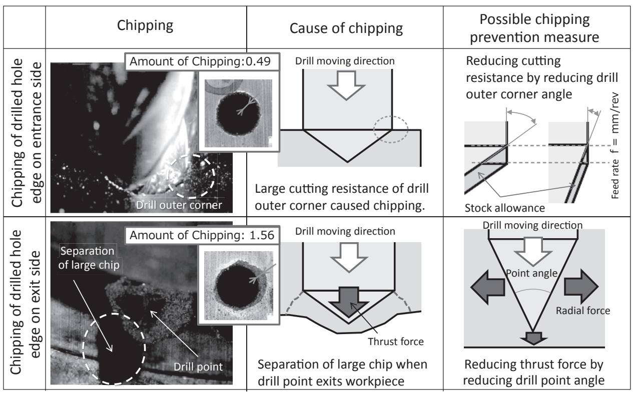


Fig. 5. Chipping of Green Compact, Cause of Chipping, and Possible Chipping Prevention Measures

At the circumferential edge of the drilled hole on the exit side, a large chip separated from the workpiece when the drill top protruded, and the conspicuously chipped hole edge remained even after the hole was completely bored. We also considered that reducing the drill point angle would disperse the thrust stress in radial directions, thereby effectively preventing the green compact from chipping at the circumferential edges of drilled through-holes on the exit side. For the product to be processed by green machining, horizontal holes must be bored through thin walls as shown in Fig. 6. Drilling these holes was expected to create excessively large radial stress and cause the stressed parts to crack.

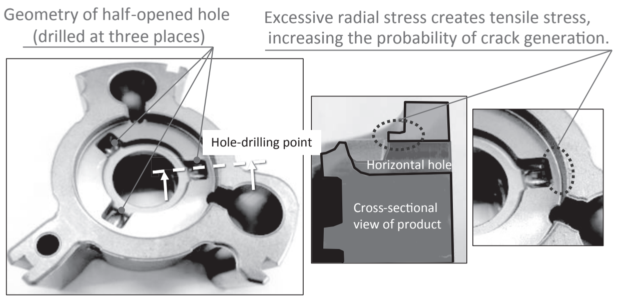


Fig. 6. Geomatry of Horizontal Hole to be Drilled by Green Machining and Cross-Sectional View of Product

To overcome such problems, we developed a new, special-purpose cutting tool shown in Fig. 7. The reduced outer corner angle of the new tool minimizes the cutting resistance, thereby eliminating chipping of the workpieces at the circumferential edge of drilled holes on the entrance side. The reduced top angle of the tool optimizes the stress distribution in the thrust and radial directions, thereby preventing the workpieces from chipping at the circumferential edge of drilled holes on the exit side and eliminating crack generation in thin walls. The newly-developed tool dramatically reduced the size of chips at the circumferential edge of the drilled hole on the exit side from 1.6 mm to approximately 0.3 mm.

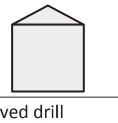
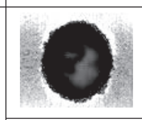
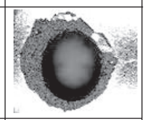
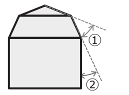
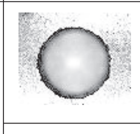
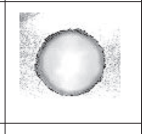
Type of drill	External view of drill	Chipping of drilled hole edge on entrance side	Chipping of drilled hole edge on exit side
General-purpose drill (for metalworking) 		 Amount of chipping: 0.49	 Amount of chipping: 1.55
Improved drill  Optimization of drill top angle 1) and outer corner angle 2) independently of each other		 Amount of chipping: 0.30	 Amount of chipping: 0.33

Fig. 7. Summary of Improved Drill Evaluation Results

2-2 Optimization of green machining conditions

To optimize the green machining conditions, we carried out process window evaluation using the drill revolution speed plotted on the horizontal axis and the feed rate plotted on the vertical axis as the parameters as shown in Fig. 8. Based on the evaluation results, we clarified the boundary condition of chipping and determined the machining conditions that assure the required quality of products.

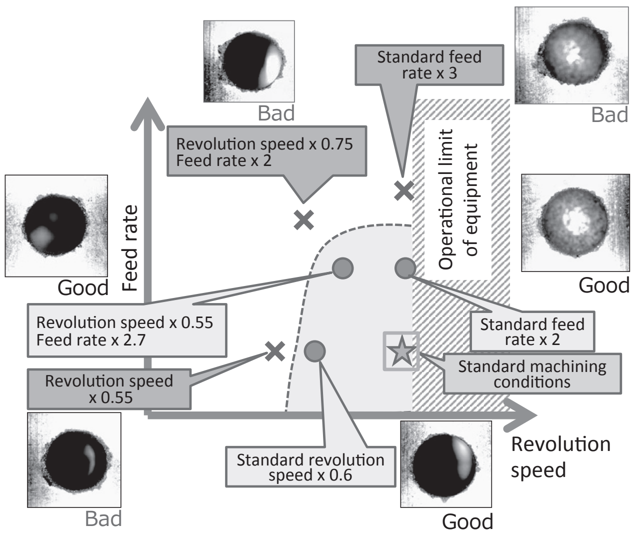


Fig. 8. Process Window Evaluation of Green Machining Conditions

With regard to another parameter, which is the state of the drill, a tool dynamometer was used to measure the thrust force imparted to the workpiece during green machining. This made it possible to more quantitatively analyze the wear/deterioration of the tool, and hence quantitatively evaluate the deterioration of the drill with time and to determine its service life (Fig. 9).

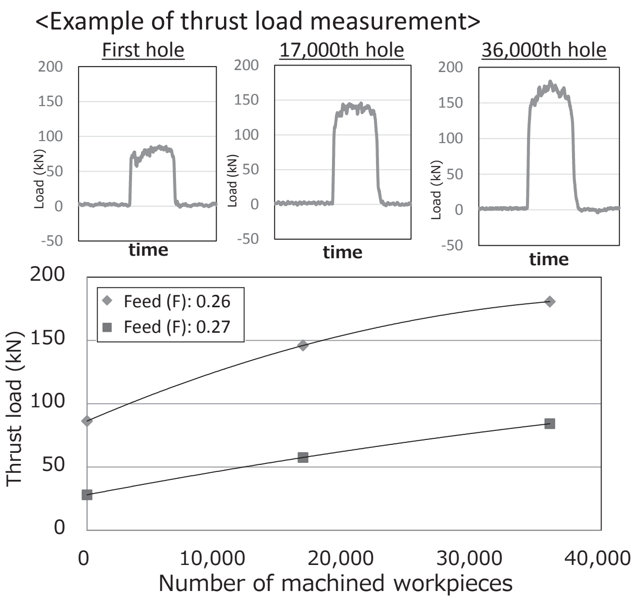


Fig. 9. Number of Machined Workpieces versus Thrust Load

2-3 Green Machining of Inner Diameter Grooves

Since the products to be processed by green machining are VVT systems with a built-in OCV, their oil passage is constructed by running a horizontal hole through the inner diameter groove as shown in Fig. 10. When the inner diameter groove is machined after the VVT rotor is sintered, it is difficult to deburr the horizontal hole at its outlet. To eliminate the necessity of deburring, we worked to apply green machining to both the horizontal hole and inner diameter groove.

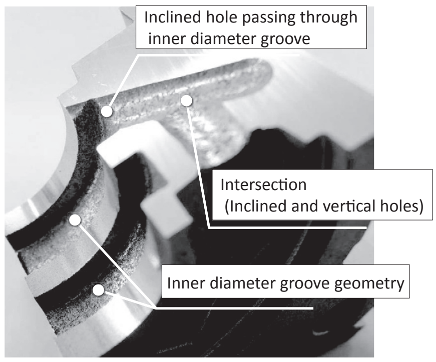


Fig. 10. Example of Product Processed by Green Machining

Inner diameter grooves are usually cut on a lathe. However, lathing a workpiece, which is a green compact, may cause cracks in the workpiece since it is strongly gripped by the chuck and is also exposed to centrifugal force created by high-speed turning. To eliminate this risk, we decided to cut the inner diameter groove on a machining center.

As an inner diameter groove cutting tool, we developed a special-purpose forming tool (having the same geometry as the groove) that can utilize low cutting resistance, a feature of green machining. The helix and clearance angles of the new tool have been optimized to suppress the generation of stress in the workpieces, thereby protecting them from chipping.

The method for inner diameter groove cutting with the new tool is schematically illustrated in Fig. 11. The newly-

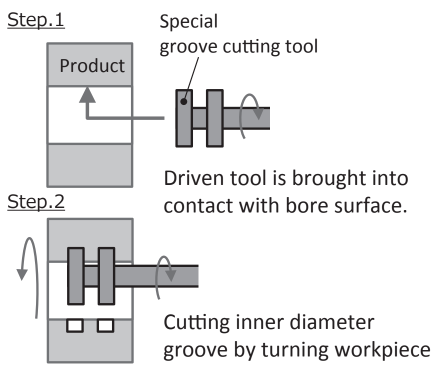


Fig. 11. Inner Diameter Groove Cutting Method (Shematic Illustration)

developed special-purpose inner diameter cutting tool enables one-chuck machining of many complexly arranged holes and inner diameter grooves.

2-4 Development of green machining line

Green machining is expected to increase productivity compared with conventional machining. However, green machining produces a buffer or workpieces in progress between processes since the machining cycle time is longer than the compacting and sintering cycle times. In practice, an intermittent production system is mainly used for green machining. In this system, green compacts made in the compacting process are temporarily placed in stock. After a predetermined number of green compacts are placed in stock, they are conveyed to the green machining process and machined. After passing through this process, they are again placed in stock. After a predetermined number of machined green compacts are stored, they are conveyed to the sintering process. Another system called a stockless production system is also used. This production system consists of two or more pieces of green machining equipment arranged in parallel in order to synchronize the green machining cycle time with the production cycle time of the compacting press.

The features of the two production systems are shown in Table 2. For this study, a stockless production system was selected. Compared with an intermittent production system, the stockless production system increases the equipment investment amount since more pieces of green machining equipment must be installed. However, the stockless production system has advantages: 1) It reduces the risk of deteriorating product quality since it eliminates the need for taking the workpieces in and out of a temporary storage shelf and therefore eliminates their contact with foreign items, 2) it does not use a workpiece storage shelf and therefore reduces the space needed for equipment, and 3) it eliminates the need for storing workpieces in progress and therefore reduces production lead time.

Table 2. Features of Production Systems (Green Machining)

Production system	Advantage	Disadvantage
Intermittent production system	· Minimizes the number of pieces of green machinig equipment (Small equipment investment)	· Increases the risk of product quality deterioration (Frequent contact with producct) · Requires large space for equipment (installation of storage shelves for work-in-progress) · Increases production lead time
Stockless production system	· Reduces the risk of product quality deterioration (Infrequent contact with product) · Minimizes space for equipment (Unnecessary to install storage shelves for work-in-progress) · Reduces production lead time	· Requires many pieces of green machining equipment (Large equipment investment) · Lowers equimpment operation rate (In case of small-quantity production)

An outline of the stockless green machining line in which the green machining equipment is operated in synchronization with the compacting press, which we have newly constructed, is shown in Fig. 12. This green machining line consists of a compacting press, a 2D code printer, several pieces of green machining equipment, and a sintering furnace. It is an automated production line in which these devices and equipment are interlinked and operated automatically. Green compacts made by the compacting press are conveyed to the green machining equipment and machined. Subsequently, a laser marker prints a 2D code on each compact. After passing the printing process, the green compacts are conveyed to the sintering process. This green machining line is a VVT parts production line that has been constructed according to the concept of one-piece flow, no contact with product, stock-less, and product traceability through 2D codes.

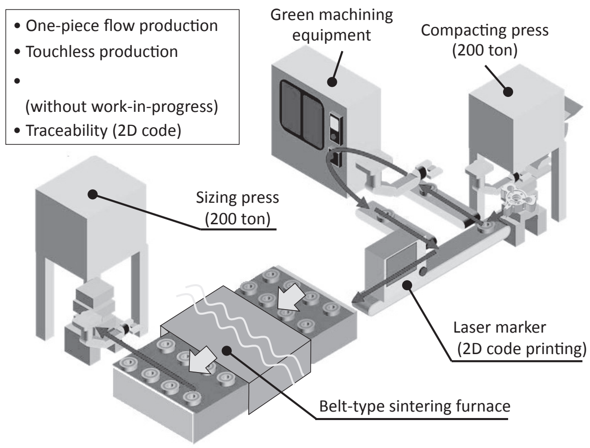


Fig. 12. Outline of Stockless Production Line in which Green Machining Equipment and Forming Press are Synchronously Operated

2-5 Ensuring product traceability

To use such challenging technology as green machining for mass production, it is indispensable to minimize the risk of product quality deterioration by correctly detecting and controlling changing points in manufacturing. In the newly constructed green machining line, a 2D code is printed on each product within the production line immediately after its green compact is machined in order to provide a manufacturing history of the product, as shown in Fig. 13. By reading the 2D code printed on each product,

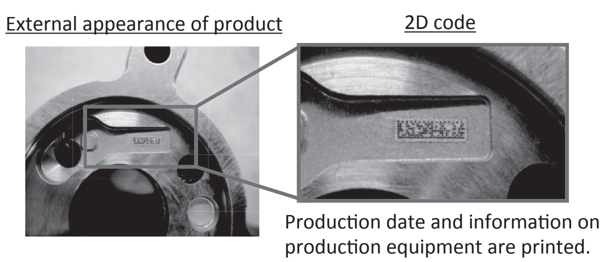


Fig. 13. 2D code (on finished product)

it is possible to identify the specific equipment used for machining the product among many pieces of equipment in the production line.

3. Conclusion

We have succeeded in constructing a VVT system production line that ensures high productivity and high product quality, under the concepts of: 1) drilling many complexly-arranged holes and cutting inner diameter grooves in green compacts by optimizing machining conditions and cutting tool geometry, 2) establishing touchless, stockless, in-line machining of green compacts by synchronizing the compacting press and machining, and 3) ensuring the traceability of each product by printing a 2D code on each green compact.

Technical Terms

∗1 Variable valve timing (VVT) system: A system used in a 4-cycle reciprocating engine to make variable a normally fixed intake/exhaust valve opening/closing timing (valve timing) and valve lift.

∗2 Green machining: The process of machining powder-metallurgically compacted green bodies before they are subjected to solid phase sintering.

∗3 2D code (2-dimensional code): A two-dimensional way of representing information. Compared with a 1D code (bar code) that represents information in only the transverse direction, the 2D code represents information in both transverse (horizontal) and longitudinal (vertical) directions, thereby making it possible to encode more bits of information and minimize the print area.

References

(1) Japan Powder Metallurgy Association AWARD (2003)
(2) Japan Powder Metallurgy Association AWARD (2007)
(3) Japan Powder Metallurgy Association AWARD (2008)
(4) Japan Powder Metallurgy Association AWARD (2016)
(5) Fine Sinter Co., Ltd., SOKEIZAI Vol.52 No.1 (2011)
(6) N. Igarashi et al., APMA2017 The 4th International Conference on Powder Metallurgy in Asia 0138

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