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Impact Forging

► Cold Forging

Improvement

► Optimization in Manufacturing Systems, Fundamentals

Incremental Forming

Alexander Brosius
Institut für Fertigungstechnik, Professur Formgebende Fertigungsverfahren, TU Dresden, Dresden, Germany

Definition

Forming process characterized by a gradual forming of the sheet, which is restricted to a small plastic zone. Nonsymmetric shapes can also be obtained by using a simply hemispheric tool in combination with a robot or a conventional CNC milling machine.

Theory and Application

Introduction

Incremental sheet forming (ISF) is a forming process similar to shear forming that allows a flexible, cost-efficient, and timely implementation of a CAD model to a real part. It was developed to meet the market demands of an efficient production of small batches, customized parts, or prototypes.

While the first attempts for manufacturing parts with a similar method are already mentioned in the patent of Leszak (Leszak 1967), the scientific investigations followed first in the 1990s by Kitazawa (Kitazawa and Nakajima 1999), thus benefiting the introduction of CAD and CAM systems and the automation with CNC machines.

Process Description and Variants

The working principle of ISF using a specific full die is presented in Fig. 1. The typical setup consists of a ball-headed forming tool, a support tool, a guided blank holder, and a sheet metal part. The sheet is clamped in the blank holder, which is free moveable in the vertical direction. The forming tool can move in XYZ direction and in most cases can rotate around Z-axis. Forming starts at the highest point of the geometry, thus moving continuously along predefined tool path to the bottom plane. As a result the sheet metal part is incrementally formed until the desired

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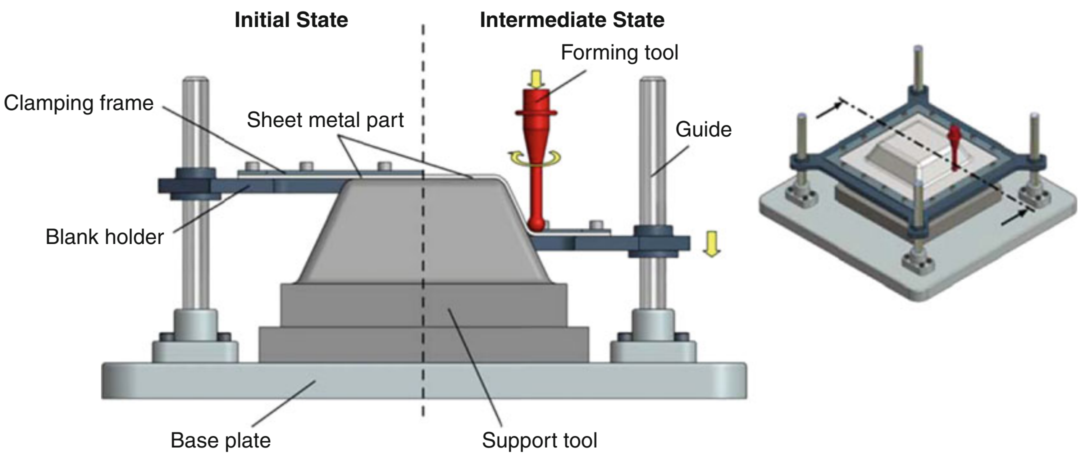


Incremental Forming, Fig. 1 Process principle of incremental sheet forming

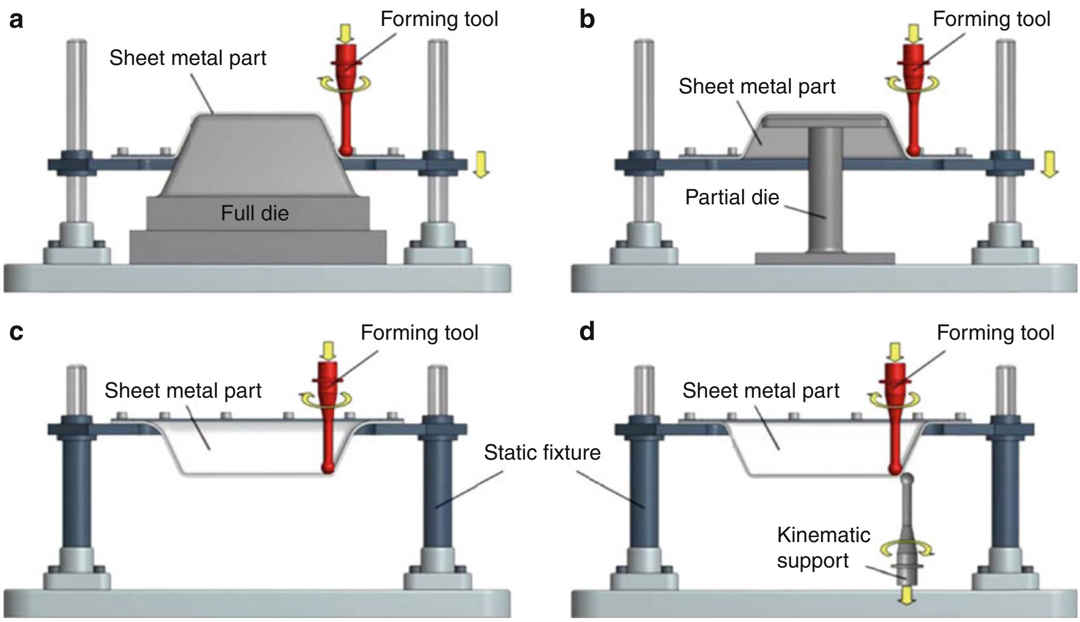
shape is obtained. The NC data for the tool path is based on the CAD model and can be generated by corresponding CAM software. The process can be carried out on any CNC-controlled machine such as a conventional milling machine, a robot, or the special-purpose machine by Amino (Akyama et al. 2000).

Depending on the type of support underneath the sheet, four variants of ISF can be distinguished (see Fig. 2). The choice of the support is the main determining factor for process flexibility, part quality, and tooling expenses. If a support is used, the highest accuracy for complex geometries is reached by applying a specific full die as shown in Fig. 2a (Junk 2003). Due to the two contact points between tool and sheet and between die and sheet, this variant is called Two-Point Incremental Forming (TPIF). Here it is required that the blank holder is free to move in vertical direction, thus descending simultaneously with the forming tool or the forming progress, respectively. Due to the fact that the forming forces are low in ISF, the full die can be made also out of cheap materials like wood or plastic.

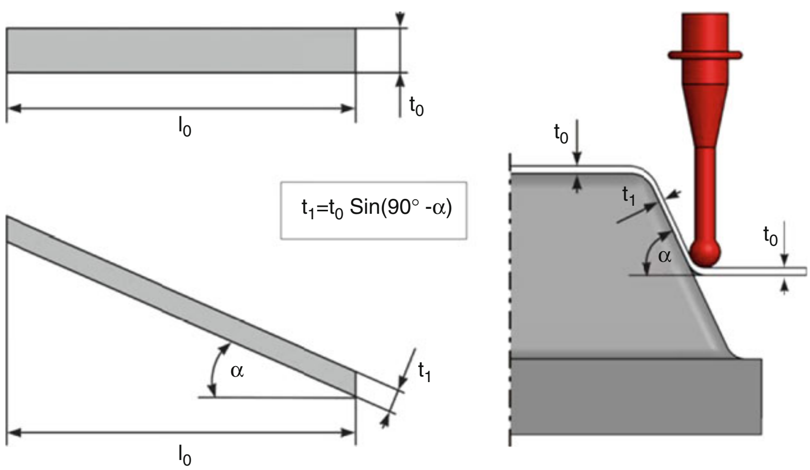
Single-Point Incremental Forming (SPIF), on the other hand, is performed without any support at all (see Fig. 2c). In this case the blank holder is fixed and stays during the entire process at the same vertical level. Here the forming tool touches only the convex side of the workpiece, accomplishing the desired shape from the bottom to the top. Consequently, SPIF is the most flexible and cost-effective variant within the ISF process. However, without any supporting die, no sharp edges or curvature changes can be produced and the resulting deviations between nominal and actual part geometry are quite high.

Seeking a compromise between tooling costs and accuracy, a partial die as illustrated in Fig. 2c can be applied. Doing so, either a specific but only locally supporting die (Draser 2006) or – considering simple shapes such as cones or pyramids – a simple supporting rod is used (Matsubara 1993).

The last variant is illustrated in Fig. 2d and is called Kinematic Incremental Sheet Forming (KISF). In this case the rigid dies are replaced by a kinematic support. The kinematic tool is moving synchronously to the movement of the main tool, thereby locally supporting the forming zone. Accordingly, this process features an increased flexibility with respect to the process variants, being dependent on rigid supports. On the other hand, kinematics are required in order to operate the secondary tool (Maidagan et al. 2007; Zhang 2008).



Incremental Forming, Fig. 2 Process variants of ISF: (**a**) Two-Point Incremental Forming (*TPIF*) using a full die, (**b**) TPIF using a partial die, (**c**) Single-Point Incremental Forming (*SPIF*), and (**d**) Kinematic Incremental Sheet Forming (*KISF*)



Incremental Forming, Fig. 3 Sine law and sheet thinning

Process Limits

In contrast to conventional sheet drawing methods, there is in ISF no material flow from the flange area. As illustrated in Fig. 3 for the forming, only the projected cross section may contribute material to the shape of the target geometry at a given time. As a consequence this leads to a systematical thinning of the sheet in steep areas of the target geometry because of the volume constancy. This relationship is referred to as the so-called sine law. According to this, a geometry with a 90° flange angle cannot be formed in one step. In practice fractures can be already observed at lower angles. Experimental investigations indicate that the range of possible flange angles is limited to lower angles. Typical ranges are between 60° and 70° for most aluminum, copper, and (HSS) steel alloys (Jeswiet et al. 2005).

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Indexing Cutting of Bevel Gears

▶ Gear Cutting

Indirect Tooling

▶ Rapid Tooling

Induction Heating

Ralf Kolleck
Institute of Tools and Forming, Graz University of Technology, Graz, Austria

Synonyms

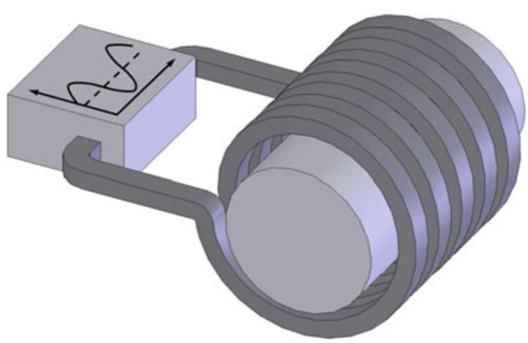
Heating with electromagnetic induction; Inductive heating

Definition

Induction heating is a method of heating electrically conductive material by internal eddy current losses.

Theory and Application

An induction heating device consists of two components, a high-frequency generator and an induction coil, the so-called inductor. An alternating voltage is applied to the induction coil which results in an alternating current in the coil



Induction Heating, Fig. 1 Generator and multiturn induction coil surrounding a workpiece circuit. In the surroundings of the induction coil, a time-variable magnetic field is produced. When an electricity-conducting component or semifinished product enters this magnetic field, eddy currents are induced in it. These eddy currents are short-circuited and result in heating, based on the Joule effect. In magnetic material, there are also so-called hysteretic losses, which contribute to the heating. The coil current, the alternating field, and the eddy currents have the same frequency (Rudnev et al. 2003). Figure 1 shows a conventional induction heating device in principle, consisting of a generator and a multiturn induction coil surrounding a workpiece.

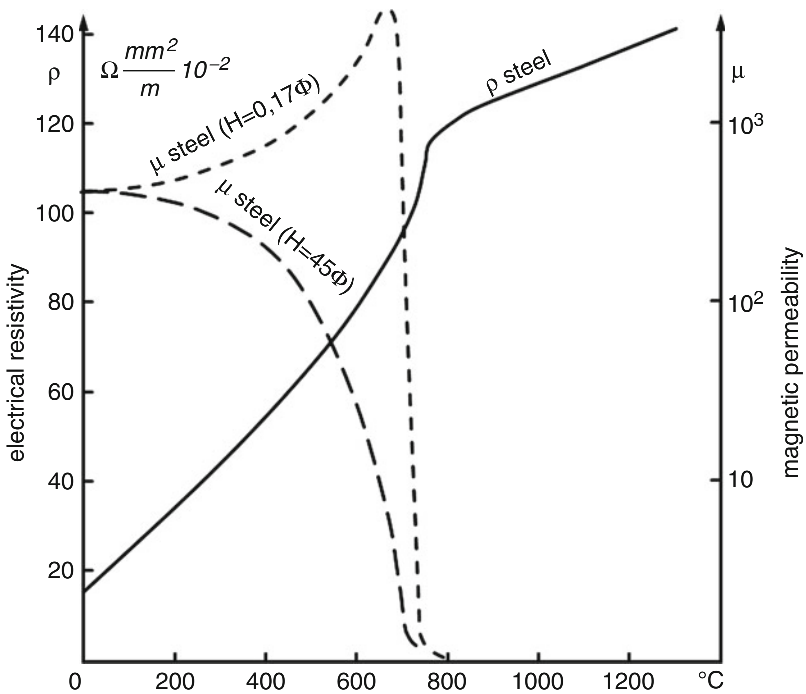
Induction Heating, Table 1 Comparison of maximum surface power densities

Type of heating	Surface power density [kW/m^2]
Convection	5
Radiation	80
Conduction of heat	200
Flame	10,000
Induction heating	300,000

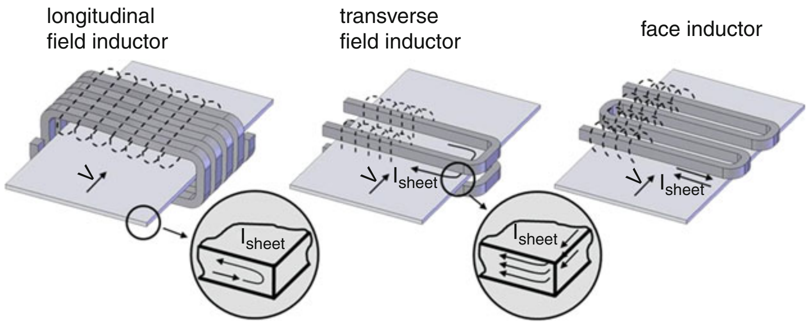
The surface power densities that can be reached by induction heating are very high compared to the heating principles convection, radiation, or heat conduction (see Table 1). This results in extremely short heating times. Induction heating has further advantages as well, such as its high efficiency, small space requirement, and good process controllability (Benkowski 1990).

The heat that is generated in the workpiece depends on the material properties, the process parameters, and the specification of the induction coil. The most important electromagnetic properties of the material to be heated are the electrical resistivity (ρ) and the magnetic permeability (μ_r), both of them depending on the chemical composition, metal microstructure, grain size, and temperature. The magnetic permeability of a material also depends on the intensity of the magnetic field (H). Figure 2 illustrates these effects by the example of steel.

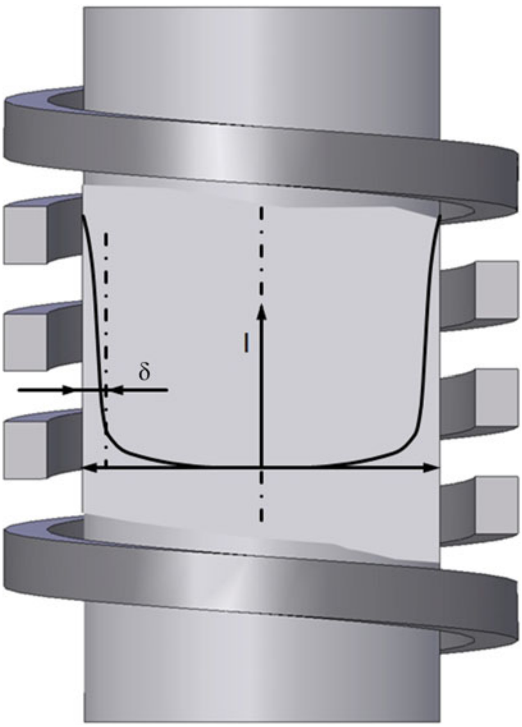
Depending on the application, there are different induction coil types in use: longitudinal field, cross field, and face inductors (see Fig. 3). The form of the inductor



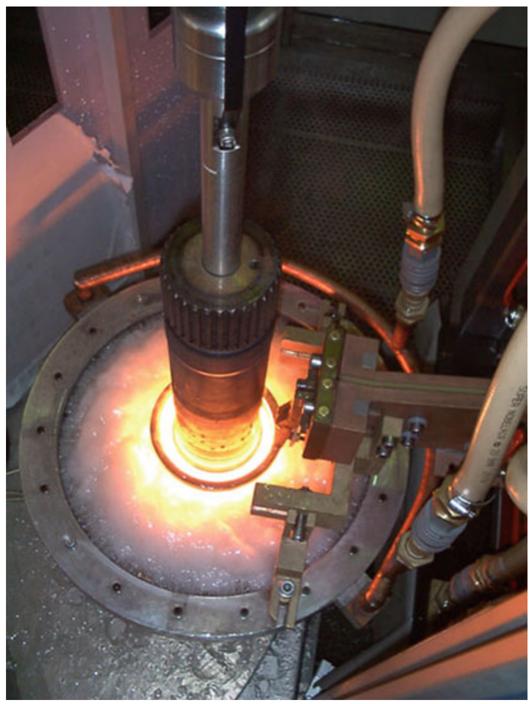
Induction Heating, Fig. 2 Electrical resistivity (ρ) and the magnetic permeability (μ_r) in dependence of the temperature (Tripmacher 1953)



Induction Heating, Fig. 3 Principle design of longitudinal field, transverse field, and face inductor



Induction Heating, Fig. 4 Current distribution and penetration depth in a longitudinal field inductor



Induction Heating, Fig. 5 Hardening of an axle shaft in a vertical feed hardening machine (Source: ITG Induktionsanlagen GmbH)

determines the position of the magnetic field in reference to the workpiece resulting in different orientation and distribution of the induced currents.

Heating a workpiece in a longitudinal field inductor, the penetration depth and thus the thickness of the heated surface layer can be controlled by the frequency of the alternating voltage.

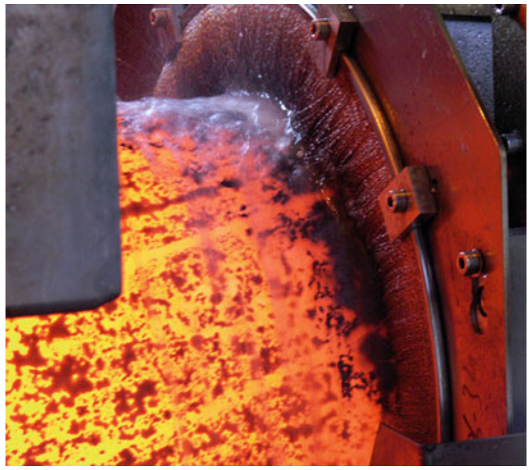
$$\delta = 503\sqrt{\frac{\rho}{\mu_r.F}}\ [\mathrm{m}] \qquad (1)$$

The penetration depth is calculated according Eq. 1 with the electrical resistivity (ρ), the magnetic permeability (μ_r), and the frequency (F). It defines the thickness of the surface layer in which 63 % of the current will be concentrated

Induction Heating, Fig. 6 Hardening and tempering of a tube (Source: ITG Induktionsanlagen GmbH)

Induction Heating, Fig. 7 Induction furnace for 300 kg steel during casting (Source: ITG Induktionsanlagen GmbH)

Induction Heating, Fig. 8 Induction coil on a tube bending machine (Source: ITG Induktionsanlagen GmbH)



Induction Heating, Fig. 9 Quenching of a tube (Source: ITG Induktionsanlagen GmbH)

Induction Heating, Fig. 10 Inductive heating of a tube right before hot forming (Source: ITG Induktionsanlagen GmbH)

(see Fig. 4). This effect is used, for example, for surface hardening.

Some examples for the applications of induction heating are (see Fig. 5–10):

- Heat Treatment
- Induction Mass Heating
- Induction Melting
- Induction Welding

A new field of application is the heating of shaped blanks for hot stamping of boron alloyed steels. First investigations show the potential for the substitution of conventional furnaces by a combination of different induction coil types (Kolleck et al. 2009).

Cross-References

▶ Hot Forging

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Inductive Heating

▶ Induction Heating

Industrial Product-Service System

Horst Meier
Ruhr-University Bochum, Bochum, Germany

Synonyms

Product-Service System; PSS; Technical Product-Service System; Technical PSS

Definition

An Industrial Product-Service System (IPS^2) is characterized by the integrated and mutually determined planning, development, provision, and use of products and services including immanent software. IPS^2 are offered in business-to-business markets and therefore address industrial applications only. An IPS^2 represents a knowledge-intensive socio-technical system (Meier et al. 2010).

An IPS^2 is a novel customized solution which uses products, services, and immanent software in an integrated manner in order to deliver a particular value instead of pure functionality to customers with an industrial background. Hence, IPS^2 aim at replacing product-focused business strategies. Furthermore, IPS^2 demand the integrated and mutually determined planning, development, provision and use of products, services, and immanent software in order to entirely expose each component's full potential. During an IPS^2's provision changing customer requirements and provider abilities are adopted dynamically (Meier et al. 2010).

Theory and Application

History

In research as well as in industry many termini are used to describe integrated products and services, e.g., Leistungssystem (Belz 1991; Schuh and Kampker 2011), hybrides Produkt (Spath and Demuß 2006), hybride Wertschöpfung (Thomas et al. 2010), Verbundsystem (Corsten 2001; Corsten and Gössinger 2007), customer solution (Tuli et al. 2007), dematerialization (Tomiyama 2001), integrated solution (Wise and Baumgartner 1999), or integrated Product-Service Offering (Lindahl et al. 2008). With regard to the present entry's keyword, the following explanations only refer to PSS or rather IPS^2.

By the end of 1999, Goedkoop et al. first published their definition of a Product-Service system (PS system). Their approach was followed by a multitude of definitions. As a result, currently a consistent definition of the term Product-Service System (PSS) does not exist. Depending on the respective author, e.g., business-to-business or/and business-to-customer markets are addressed, the importance of products and services are weighted differently or environmental improvements are particularly aimed at (Goedkoop et al. 1999; McAloone and Andreasen 2002; Manzini and Vezzoli 2003; Mont 2004; van Halen et al. 2005; Steinbach 2005; Tukker and Tischner 2006a; Aurich et al. 2006; Meier et al. 2010).

Initially, the research on PSS was mostly driven by aspired environmental improvements. In retrospective, the interrelation between PSS and improved environmental impact is debatable. According to Tukker and Tischner, the assumption that PSS equal sustainability is just a myth. Instead, the authors explain that in general PSS own the potential to reduce waste materials as well as the consumption of resources, but only if such a potential has been exposed during a PSS's development (Tukker and Tischner 2006b). As per Mont, PSS effectively contributed only in very few cases to a modified product design and thereby a better end-of-life-management (Mont 2004). Goedkoop et al. state that the ecologic potential of every PSS has to be assessed individually (Goedkoop et al. 1999).

Aside from environmental benefits, the differentiation from competitors due to customized offers and the increase of profit margins are associated with PSS as well (Goedkoop et al. 1999; Mont 2004; Baines et al. 2007; Tuli et al. 2007). An analysis of such advantages revealed that offering PSS demands an appropriate amount of financial resources, high organizational and management skills, as well as a systematic development. Furthermore, it is of particular importance to know a customer's business which means to distinguish between customers who really ask for novel, nontraditional business offers and those who are advised best to focus on a product-centered business model (Goedkoop et al. 1999; Mont 2004; Van Halen et al. 2005; Tukker and Tischner 2006a und 2006b; Tuli et al. 2007; Baines et al. 2007; Laurischkat 2012).

While most authors focus either on environmental, economic, or design-related aspects of PSS, the SFB/Transregio 29 holistically studies IPS^2 since 2006. In this regard, over 30 researchers jointly investigate, e.g., IPS^2 business models, IPS^2 development, organizational and capacity planning of IPS^2, etc.

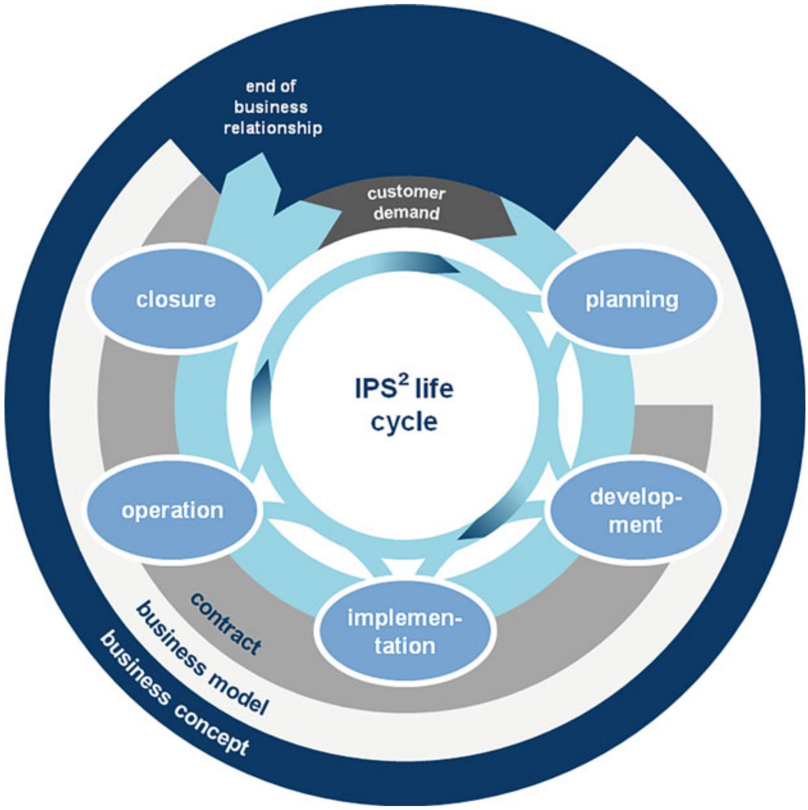
Services Versus Products

Whereas it is common understanding that the notion "product" describes a physical artifact, in service research a standardized definition of the term service does not exist. Nonetheless, the majority of authors explain services with the aid of three dimensions or rather three constitutive characteristics which result from those dimensions. With regard to the "capability dimension" a service is explained as the ability and willingness of a provider to render the service in question. Such ability is considered intangible. Therefore, the first constitutive characteristic used to define a service is "intangibility." With reference to the "process dimension" a service is characterized by its simultaneous consumption and production as well as by the integration of so-called external factors. Examples for such factors are customer's personnel, goods, rights, or information. In this regard, the term "external" points up that a service's provider is never part of its customer's company. Hence, the second and third constitutive characteristics, referred to as "uno-actu-principle" and "integration of external factors," result from the process dimension. The definition of the notion service which follows from the "result dimension" is the most discussed one. While some authors argue that a service results in tangible and intangible outputs, others persist that a service has an intangible output only (Hilke 1989; Knoblich and Oppermann 1996; Corsten 2001; Kleinaltenkamp 2001).

Life Cycle of an IPS^2

The life cycle of an IPS^2 consists of the following five phases: IPS^2 planning, IPS^2 development, IPS^2 implementation, IPS^2 operation, and IPS^2 closure (see Fig. 1) (Meier et al. 2011).

During the IPS^2 planning at first customer's demands are identified. Based on that, specific customer requirements are derived from such demands. Furthermore, the form of contract is defined. With regard to the aforementioned requirements it is of great importance that those requirements do not relate to particular products



Industrial Product-Service System, Fig. 1 Life cycle of an IPS^2 (Meier et al. 2011)

or services. At this point, only functions and characteristics are specified (Meier and Uhlmann 2012).

During an early phase of the IPS^2 development one or several concepts are developed based on the requirements which result from the IPS^2 planning. Each concept represents an IPS^2 on an abstract level. During an advanced development stage products and services, which were jointly described with the aid of a certain concept, are now further detailed separately. As a result, the IPS^2 which has been offered to a particular customer is described in detail (Meier and Uhlmann 2012).

During the IPS^2 implementation several tasks are conducted which are necessary to put an IPS^2 into action in the future. This includes the production of products, logistical processes which are connected with the delivery of products, the build-up of resources necessary to render one or several services, and after all the initial operation of the IPS^2 (Meier and Uhlmann 2012).

During the IPS^2 operation products, services and immanent software are jointly provided to a customer. Furthermore, changing customer requirements and provider abilities are adopted dynamically (Meier and Uhlmann 2012).

The IPS^2 closure contains the ending of the contractual relationship between a provider and its customer (Meier and Uhlmann 2012).

To offer a certain combination of products and services advantageous to all partners, dynamic business models are necessary considering the special properties of IPS^2 across the life cycle. An IPS^2 business model covers a value proposition, the value architecture, and a revenue model. The value proposition describes the benefits and therefore the value a customer or a value partner gains from the business model. The aim of the value architecture is to create the promised customer benefit in an efficient way. The revenue model contains a description of a provider's sources and ways of revenue generation (Stähler 2002).

Value Propositions in the Context of IPS^2

In the context of PSS especially Tukker and Tischner clarified the shifting of ownership between a provider and its customer by introducing product-oriented services, use-oriented services, and result-oriented services. According to Tukker and Tischner a product-service generally represents a value proposition consisting of a mix of products and services used to jointly fulfill final customer needs. Whereas in the context of product-oriented services the business model is still geared toward the sales of products with some additional services, in the context of use-oriented services the product stays in the ownership of the provider. In this regard, the product itself is made available to one or even several customers in a different, nontraditional form. In case of result-oriented services the provider and its customer agree on a certain result without specifying a particular product (Tukker and Tischner 2006a).

Since services and products are considered equal in the context of IPS^2, product-oriented services are explicitly excluded from an IPS^2's definition. Use- and result-oriented services, however, represent value propositions which entirely apply to IPS^2 and are most commonly used in industrial applications.

Cross-References

▶ Product Life Cycle Management
▶ Sustainability

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Industrial Robot

► Robot

Information Management

Winnie Dankers
Laboratory of Design, Production and Management, University of Twente, Enschede, The Netherlands

Definition

Information management (IM) is the management of the processes and systems that create, acquire, organize, store, distribute, and use information. The goal of information management is to help people and organizations access, process, and use information efficiently and effectively (Detlor 2010).

Theory and Application

Data, information, and knowledge are extremely important commodities for all organizations. The effective utilization of these "commodities" is seen as one of the most critical factors for business success (Minkus et al. 2007). In product development cycles, the effective utilization and application of information and knowledge commodities, e.g., enables the generation of feasible design alternatives and assists the decision-making process, which ultimately determines the success of the designed artifact (Hicks et al. 2002). By realizing proper management of these commodities within the organization, companies can thus obtain significant improvements in performance and efficiency.

Although data information and knowledge are closely related and are often considered to be synonyms, there are some differences between them that hold the key to better enabling their effective identification, capture, and reuse (Ammar-Khodja and Bernard 2008). Within the context of engineering design, information is generally considered to be comprised of a number of data parts and of their descriptions, and knowledge is the ability of an individual to understand information and to describe the manner in which it handles, applies, and uses it in a given situation (Court 1995).

Consequently, information management (IM) is about documents, CAD drawings, spreadsheets, program code; means ensuring access, security, delivery, and storage; and deals exclusively with explicit representations. It should not be confused with knowledge management (KM), which rather recognizes value in originality, innovation, agility, adaptability, intelligence, and learning; seeks to leverage the capacity of the organization in these areas; and is concerned with critical thinking, innovation, relationships, exposure to ideas, patterns, competencies, and collaboration (Gu 2004).

Information Technology

Information technology (IT) is the technical medium upon which information is housed, accessed, retrieved, distributed, and used and is therefore an important aspect of information management. Often, organizations have several information resources, systems, and IT solutions that need to be managed. From an organizational perspective, the management of information technology is a major component of any IM plan. It is with this perspective where associated terms like information systems management and information technology management come from (Detlor 2010). Nevertheless, the equation of information management with the management of information technology as such is too confined.

Information Management Systems/ Information Systems

Attempts to improve the information management within an organization generally involve either the expansion of the amount of information that is managed or the implementation of additional or new information management systems. These information management systems (or information systems (IS)) are generally commercial software applications or suites that are based on standards, languages, and processes and include a variety of tools and methods to support the specific activities of information management. Due to the different backgrounds these systems have been developed from, their focus is on the management of different types of information. Therefore, in product development cycles, usually a large number of different systems are used.

Some of the most applied systems for information management include those for (Hicks 2007):

- The management of sources of information (e.g., records and database management systems (RDBMS), document management systems (DMS), and product data management systems (PDM))
- Information management for business processes (e.g., customer relationship management (CRM), accounting and payroll systems, inventory systems, and logistics)
- The integration of the IS infrastructure (e.g., material requirements planning (MRPI), manufacturing resource planning (MRPII), and enterprise resource planning (ERP))

PDM

Product data is the data of a product (in-design) that is captured in computer-aided design (CAD) and computer-aided manufacturing (CAM) models, drawings, and other related documents. From an engineering point of view, the focus in information management has traditionally been on capturing and managing versions of, and changes to, this CAD and CAM information. Different versions are ineluctable when multiple engineers concurrently work on the development of a product (family). Consequential of the engineering demand for managing product data are so-called Product Data Management (PDM) systems. A PDM system is a product structure and data manager that organizes and stores all the product data that is available in an organization. It, among others, manages the various product configurations available, it provides functionalities for versioning and linking various parts and documents in the product structure, and it ensures the management of data status. PDM systems can also contain the functionality to provide the right available data at the right time to the right user (Eynard et al. 2004).

MRPI, MRPII, and ERP

MRPI, MRPII, and ERP originally originated from the call for systems to monitor and improve the flow of financial resources. Enabled by the development of early computers, material requirements planning (MRPI) systems – the precursors of ERP systems – were, for example, able to determine the most economic order quantity of product-parts and the most economic point of reordering (Jacobs and Weston 2007). During the years, the demand for integration of other functional information – including information on materials, machines, and human relation – increased, first resulted in manufacturing resource planning (MRPII) systems and subsequently in current ERP systems. These systems are seen as business management systems that have the function to integrate all facets of the business, managing the flow of action in the entire organization. The term ERP was established in the early 1990s by the Gartner Group (Wylie 1990) and includes criteria for evaluating the extent that software is actually integrated both across and within the various functional silos of an organization. Over the past few years, ERP has been implemented by almost every organization to improve competitiveness.

Cross-References

- ▶ Decision Making
- ▶ Knowledge Management
- ▶ Product Development
- ▶ Product Life Cycle Management

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In-Process Inspection

Guido Tosello
Department of Mechanical Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark

Definition

The set of hardware, software, procedures, and activities that are integrated in the manufacturing system in order to provide measurements of dimensional characteristics of manufactured products and tools during the manufacturing process.

Theory and Application

In general, the main goal of inspection is to ensure the functionality of workpieces, products, and testing devices and thus ensuring economical aspects. Inspection allows the measurements of dimensional characteristics of components and the comparison of the results of those measurements with the product specifications (ISO 2011a). ▶ Metrology (ISO 1994) is employed as the inspection process for experimentally obtaining information about the magnitude of a quantity. Such information gained from measurements will provide specific knowledge on actual parameters of the inspected manufacturing system and product.

In particular, whenever an inspection system is an integral part of the manufacturing system (including its hardware, software, and procedures), an in-process inspection is realized. As such, the inspection is carried out during the manufacturing process (i.e., in-process), and the information generated during the inspection (e.g., measurement data) is collected simultaneously with the manufacturing process.

In-Process Inspection System Characteristics

In today's industrial processes, metrology and quality control procedures are an integral part of the whole manufacturing system framework. In the field of manufacturing metrology, whenever an inspection system is an integral part of the manufacturing system (including its hardware, software, and procedures), an *in-process inspection* is realized. As such, the inspection is carried out during the manufacturing process (i.e., in-process), and the information generated during the inspection (e.g., measurement data) is collected simultaneously with the manufacturing process.

The development of production technology is directed towards an improved quality of products and increased productivity. In this context, the *in-process inspection* has a tremendous impact on the overall quality of both process and products. The measuring data collected are used to verify quality and tolerances of products at the same time they are manufactured; therefore, trends and outliers can be spotted before defective products are produced. *In-process inspection* data are often used by the manufacturing system control unit in order to modify the process parameters, to realize a new and optimized process configuration, and as a consequence to manufacture virtually defect-free products. Such **closed-loop manufacturing system usually combines product-related inspection data with process measurements data** (i.e., measurements performed on process parameters) in order to monitor and control the process itself. The result is a highly optimized and repeatable manufacturing process capable of making products consistently in tolerance (i.e., defect-free production). Furthermore, as far as the product quality is concerned, an in-line metrology can be used to reduce the stability requirements of the process by classifying and sorting products depending on their properties in order to better match with counterparts in subsequent assembly steps. Finally, information generated by the in-line inspection system can be used to increase the knowledge about the process itself and therefore to improve product quality through process optimization.

As such, *in-process inspection* follows the general principles of inspection. Further, due to the integration of *in-process inspection* into precision manufacturing, the realization of product with tight tolerances and virtually zero defects, in-process inspection systems are characterized by the need of performing accurate measurements in a specific timeframe, typical of the manufacturing process cycle time. The metrology of the in-line inspection system should have the following characteristics (Kunzmann et al. 2005):

- **Adequacy**: the measuring system should have an adequate ► measurement uncertainty (the ratio of 1:5–1:10 between uncertainty and tolerance is advisable) and the ► traceability of measurements ensured.
- **Proximity**: the measuring system should be as close as possible to the process to be controlled, to increase reaction speed, minimize work in progress, and ramp up times.
- **Reliability**: the measuring system should be based on a reliable and robust technology, as well as be verified regularly according to well-defined and established procedures, such as the ISO 10360 series for ► coordinate measuring machines (e.g., ISO 2010, ISO 2011b).

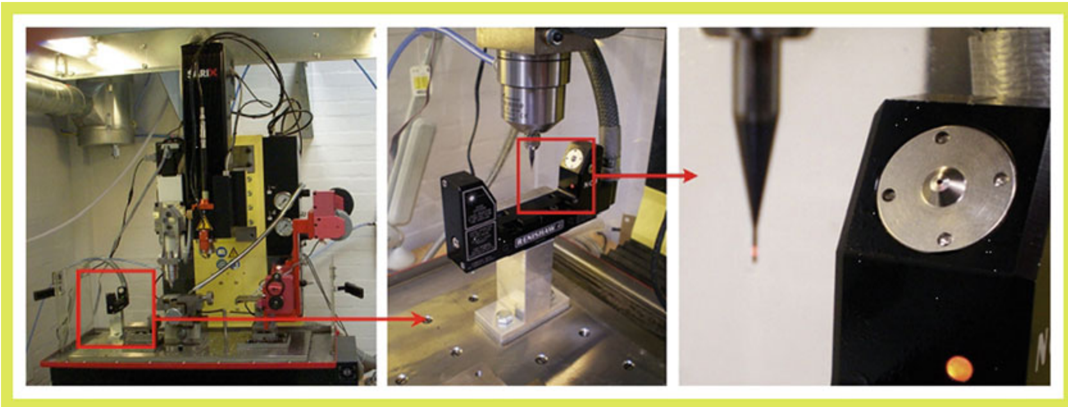
An in-line inspection system is an integral part of the manufacturing system and therefore has to be included in the global cost and benefit analysis when evaluating the overall investment of the production facility. Besides the overall cost of the production equipment, the following economic factors specifically related to the metrology system should be included in the economic analysis (Kunzmann et al. 2005):

- Investment (instrument, environment)
- Labor, maintenance, calibration, and training
- Energy
- Process time
- Type A damage (rejection of good parts)
- Type B damage (acceptance of bad parts)
- Increased process knowledge and know-how

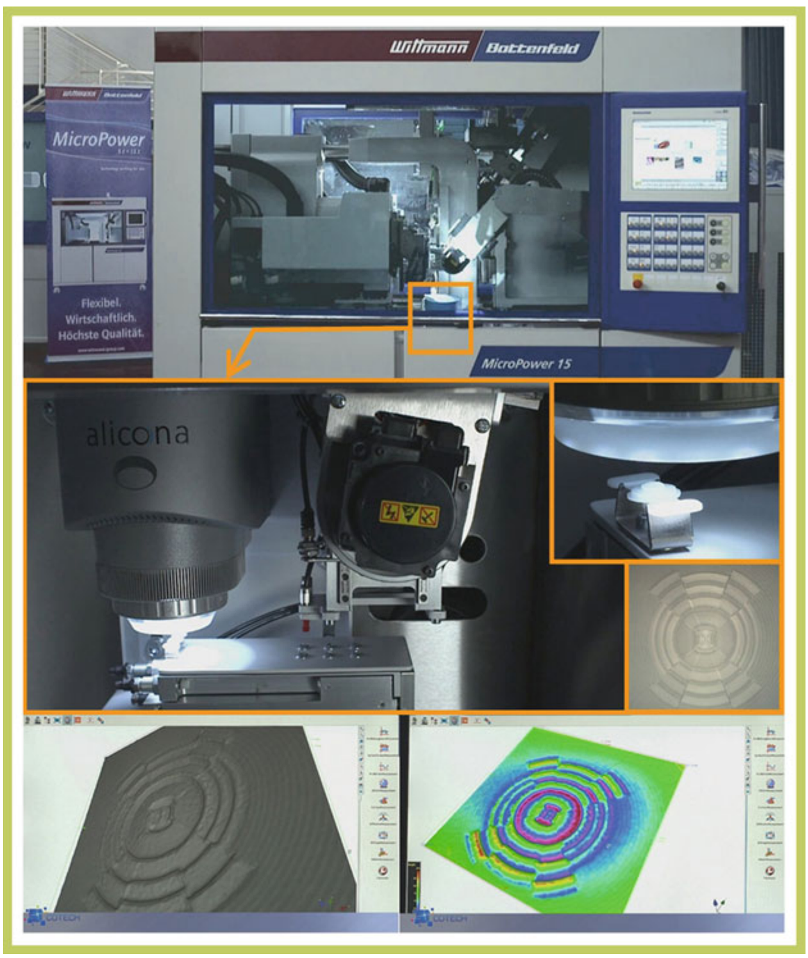
Applications of In-Process Inspection Systems

In-process inspection systems can be found in different manufacturing scenarios such as:

- **Production technology** (e.g., machining)
- **Replication processes** (e.g., injection molding)



In-Process Inspection, Fig. 1 Example of in-process inspection system integrated on a machine tool: microelectrical discharge machine (µEDM) with integrated in-process inspection of the microelectrode diameter and length by a measurement laser device. The measurement is used during both (1) the electrode manufacturing (i.e., shaping) by the dressing wire electrical discharge machining unit to reach the designed electrode diameter and (2) during µEDM of the workpiece to update the CNC machining program with new wear compensation data. Higher machining accuracy and shorter machining times are therefore achieved



In-Process Inspection, Fig. 2 *Top*: micromanufacturing unit based on a microinjection molding machine with handling robot. *Middle*: 100 % quality control of polymer microproducts by measurement using focus variation micrometrology instrument (production cycle and measurement scanning time: 3–5 s). *Bottom*: 3D evaluation of measured data set points (Images courtesy of Alicona GmbH and Wittmann Battenfeld GmbH)

- **Assembly lines** (e.g., medical sector, where products are manufactured in a clean-room environment, assembled, inspected, sorted, and packaged in the same manufacturing cell to avoid any contamination and to guarantee 100 % defect-free production)

Recent examples of in-process inspection can be found in the following applications:

- Five-axis milling machines with an integrated tactile coordinate measuring machine
- Laser machining where a laser used for structuring is integrated with a laser employed for measurement (Schmitt et al. 2011)
- Microelectrical discharge machines with integrated electrode diameter measurements laser device (see Fig. 1)
- Injection molding machines with an optical (e.g., CCD camera, focus variation) measuring device and automated product handling (see Fig. 2)
- Crankshaft bearings manufactured with a linear capacitive sensor system in the automotive industry (Kunzmann et al. 2005)
- Magnetorheological finishing of aspheric lenses with interferometric measurements integrated in the process (Kunzmann et al. 2005)
- Large-part (e.g., car body) manufacturing line with in-process metrology station composed by optical sensors mounted on a rigid frame (Kunzmann et al. 2005) and focus variation sensor mounted on robots or using structured light projection (Couweleers et al. 2003)
- Laser-based in-process roundness measurement integrated in a turning process (Mekid and Vacharanukul 2011)
- Textile production machine with integrated vision system for nondestructive fabric inspection and defect detection (Neumann et al. 2011)
- Assembly station of a diode-pumped solid-state laser including a machine vision robot equipped with a high-resolution camera (Schmitt and Pavim 2009)
- Composite material production with integrated in-line machine vision system using a diffuse illumination (Mersmann 2011)
- Automated deburring of aeroengine components using a vision system-driven cutting tool (Jayaweera and Webb 2011)

Cross-References

▶ Coordinate Measuring Machine
▶ Error
▶ Measurement Uncertainty
▶ Metrology
▶ Production
▶ Statistical Process Control
▶ Tolerancing
▶ Traceability

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Inspection (Assembly)

Günther Seliger
Technische Universität Berlin, Institut für Werkzeugmaschinen und Fabrikbetrieb Montagetechnik und Fabrikbetrieb, Berlin, Germany

Synonyms

Quality control

Definition

Inspection is an *examination of a product, process, service, or installation or their design and determination of its conformity with specific requirements or, on the basis of professional judgment, with general requirements.* (DIN EN ISO/IEC 17020). The process of inspection includes determining whether or not a part, product, or batch is free from faults or "*nonconformity*" as it is called in DIN EN ISO 9000. A fault in this notion is a departure from prescribed textures, tolerances, sizes, behavior, or other dimensions of quality. The level of quality which should be accomplished is written down in specifications or generally accepted standards.

Inspection can be seen as a part of maintenance which is described in DIN 31051 "Fundamentals of maintenance." The term however does also describe the process of controlling the quality of finished or semifinished products during the assembly process.

Due to the fact that there are other wiki entries which cover the maintenance topic, this article describes inspection as a part of quality control for assembly products. It is important however to understand the inherent differences between the terms in Fig. 1. Inspection is always just a part of a system of tools which help to ensure a certain standard.

Theory and Application

Motivation for Performing Inspection

Assembly is the process of putting together parts and components to make a complete product. While there are many sources for faults in this process, it is also crucial for the quality and cost performance of the producing company. Therefore a quality control is very important not only to ensure a certain level of product quality but also to enable the company to make profit.

That is why the process of inspection has to fulfill multiple goals. On the one hand it is urgent to make sure that an assembled product will work within certain parameters. Therefore it is necessary to guarantee the function of each and every component of the product plus their connections. On the other hand there is rarely a need for a perfect quality in all parts. If the product and/or crucial parts comply with a certain, prescribed level of quality, it is good.

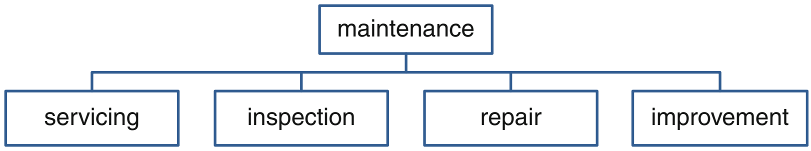
Summed up there is a need for a quality balance of acceptable versus unacceptable detail in a component or product. The inspection body has to ensure a certain level of quality and low costs at the same time. Therefore it has to have knowledge about crucial parameters of the product and assembly processes.

Causes and Results of Assembly Faults

There are several causes of assembly faults. Liu et al. classified assembly defects in four categories:

- Improper design.
- Defective part.
- Variance in assembly system.
- Operator mistake.

Inspection (Assembly), Fig. 1 Methods of maintenance according to DIN 31051



Besides this description of the causes for assembly faults, it sometimes makes sense to look at the subject from another point of view and to name the results of a faulty assembly:

- Faulty parts are assembled.
- Wrong parts are assembled.
- Some parts are missing completely.
- The connection between parts is inaccurate or incomplete.

The aim of inspection is to identify a faulty assembly and to correct the root causes.

Application

An inspection can be done in several ways and is therefore classified depending on how the work has to be performed. Common terms which are used in this context are manual inspection and automated inspection.

Manual inspection is inspection performed by an inspector with hand-operated equipment. It is used to find faults in items of high complexity and/or of low number. In these cases it would be too expensive to use an automated system for inspection. That is why automatic inspection is usually seen when applying a quality control to a large number of items.

In any cases the function of inspection is the same: The inspector or the inspecting automated system has to find nonconformities in the item which can be done by measuring and gauging. Nondestructive and destructive examination can be used to determine whether a product has inherent flaws or not. Common methods for testing – besides others – are visual or microscopy inspection, X-ray or radiographic testing, ultrasonic testing, acoustic emission testing, and thermographic inspection.

Inspection is often performed at different levels of completion during the assembly process. This is necessary to enable the inspection body to detect faults when they occur and to correct them before they cannot be adjusted anymore. Usually that means that crucial parts, construction groups, and the whole product are examined at some point of the assembly process. At least a final inspection should be planned after the product is fully assembled to ensure that quality requirements are fulfilled.

The inspection process shall be documented to enable the management to analyze and evaluate the results and to establish corrective steps if necessary. Therefore the *inspection body shall be organized and managed so as to enable it to maintain the capability to perform its inspection activities* (DIN EN ISO/IEC 17020). An inspection body that is somehow integrated badly in organizational structures is likely to lack the ability to find a high percentage of faults which unavoidably occur during the assembly process.

The process of inspection covers the following workflow (based on DIN 31051):

- Get and document the filing; analyze the filling content.
- Prepare a plan to determine the current state of your object of interest – place, time, method, and equipment of the planned inspection process should be mentioned here.
- Prepare the execution.
- Check the equipment at your working environment as well as safety devices which may be necessary.
- Last check your preparation and make sure that all of the previous steps are taken.
- Inspect the item which means that at this point certain parameters of a product are examined.
- Collect data for presenting a correct and comprehensive view of the current state.
- Evaluate the data.
- Check for possible faults which could have happened in the inspection process.
- Determine which possible solutions exist for a wrong or faulty assembled product.
- Choose one of the solutions above.
- Provide feedback about the results.

Cross-References

▶ Quality Assurance

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Inspection (Precision Engineering and Metrology)

Guido Tosello
Department of Mechanical Engineering,
Technical University of Denmark, Kgs. Lyngby,
Denmark

Definition

In the field of Precision Engineering and Metrology, *inspection* can be defined as the set of hardware, software, procedures, and activities that can provide measurements of geometric characteristics of physical manufactured products.

Such geometric characteristics can refer to absolute dimensions (e.g., diameter) and form (e.g., free-form surfaces), to tolerances of dimensions and form (e.g., flatness), as well as surface parameters (e.g., average surface ▶ roughness).

Theory and Application

The main goal of *inspection* is to ensure the functionality of workpieces, products, and testing devices and thus ensuring economical value of products. As such, the main objective of *inspection* in the field of Precision Engineering and ▶ Metrology is to quantify the dimensional characteristics of components by means of measurements and to compare the results of those measurements with the product specifications (ISO 8015 2011).

Inspection is today very closely connected into the manufacturing process as a whole, including small/medium/large fabrication series, prototyping, research and development, as well as in standardization, accreditation of calibration laboratories, and for trade purposes.

The task of *inspection* is the detection of quality features of a measured object. A measurement object can be a manufactured workpiece, a standalone product, a component of a more complex assembly, an interchangeable part such as a tool, a complete system such as a machine or a measuring device. The term *inspection* is closely related with the concept of the testing of products. As a matter of fact, inspection represents the assessment of whether a characteristic of an object corresponds with the required specifications.

The testing can be conducted applying direct measurements or comparative assessment using calibrated artifacts or gages. The inspection is executed by means of measurements. The measurable quality features of a product are of different kinds such as material characteristics, geometry, and function of a product. In particular, the inspection of geometrical characteristics is the most frequently used procedure in the inspection of manufacturing system and products, and covers the large majority of the test and measurement tasks.

Typical inspection tasks of important workpiece characteristics for the functionality of a product are:

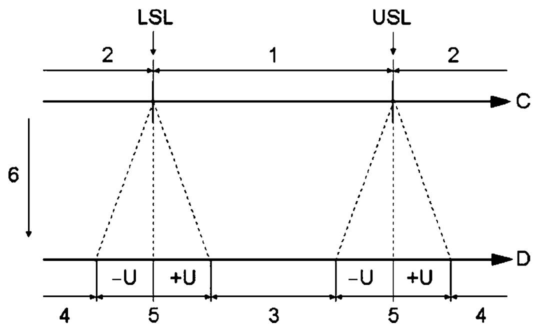
- Form measurements (e.g., squareness, flatness, etc.) (ISO 1101 2004)
- Distance measurements (e.g., hole depth, groove width, etc.)
- Orientation measurements (e.g., parallelism, perpendicularity, etc.) (ISO 1101 2004)

- Surface properties (e.g., root mean square roughness, bearing curve parameters, etc.) (ISO 4287 1997)

An inspection system is composed by a number of entities:

- **Hardware**, i.e., the measuring device (e.g., ► coordinate measuring machine, roughness tester, optical microscope, white light interferometer, gage/calibrated object, etc.) employed for the inspection (a complete inspection of a component may need more than one measuring device or gage).
- **Software**, including the control system of the measuring instrument and the collection/evaluation/representation of the measuring data (these two functions can be either performed by the same software or by two or even more different softwares).
- **Procedures and activities**, i.e., the set of conditions to be complied with and of actions to be performed in order to carry out the inspection; the methodology of inspection needs to be highly specified; therefore, all aspects of the inspection are thoroughly described (e.g., the instrument to be employed, the environmental conditions during the measurements, the number of repeated measurements to be performed, the number of items to be measured, the number of probing points, the fixture to be employed, and how the component has to be fixed on the measuring instrument, etc.).

The result of *inspection* is the assessment of whether a particular tolerance/specification for the workpiece under inspection is achieved. In this process, it is of paramount importance that the estimated uncertainty (JCGM 100 2008; ISO 14253–2 2011) of the performed measurement is taken into account when providing evidence for conformance or nonconformance with specification. Such rule of conformity has been established and is described in the current regulation by the standardization body (ISO 14253–1 1998). The uncertainty of measurements carried out on manufacturing process inspections reduces the conformance and nonconformance zones (see Fig. 1). When the uncertainty in a measurement is evaluated and stated, the fitness for purpose of the measurement can be properly judged. A measurement carried out in manufacturing process and product inspection should have an uncertainty of measurement of 10–20 % of the tolerance range: U = T · (0.1 . . . 0.2) (Knapp 2001). In case of inspection for precision manufacturing and precision engineering applications, the 10–20 % U/T ratio could be reduced to 1–5 % U/T to ensure that the measurement uncertainty is sufficiently small to be able to verify the specified tolerances and to not introduce a too large spread and bias in the process quality control. The risk is to introduce an additional error during the inspection if measuring instruments are involved in production process/product assessment and their uncertainty of measurement cannot be neglected in the evaluation of results (Weckenmann and Rinnagl 2000). In case the uncertainty of measurement overlaps with process deviation, manufacturing processes are assessed as being worse than they really are, invalidating the inspection process and hampering its economical function.



Inspection (Precision Engineering and Metrology), Fig. 1 Rule of conformity: tolerance verification reduction due to the measuring uncertainty of the instruments employed during the inspection. *C*: workpiece design/specification phase, *D*: manufacturing process verification phase, *1*: specification zone (in specification: tolerance T), *2*: out of specification, *3*: conformance zone, *4*: nonconformance zone, *5*: uncertainty range, *6*: increasing measurement uncertainty (*U*)

Cross-References

► Coordinate Measuring Machine
► Form Error

▶ Measurement Uncertainty
▶ Metrology
▶ Roughness

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Installation

▶ Assembly

Integration

▶ Synthesis

Interactive Manufacturing

▶ Emergent Synthesis

Interferometric Measurement

▶ Interferometry

Interferometric Metrology

▶ Interferometry

Interferometry

Christopher J. Evans
Department of Mechanical Engineering and Engineering Science, The William States Lee College of Engineering, University of North Carolina at Charlotte, UNC Charlotte, Charlotte, NC, USA

Synonyms

Interferometric measurement; Interferometric metrology

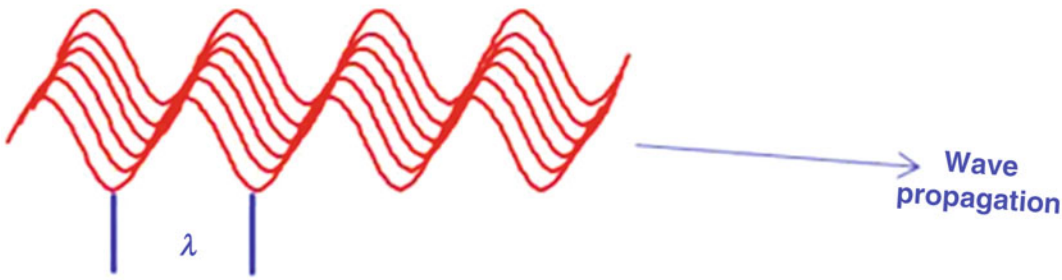
Definition

Interferometry is a process in which the superposition of two or more waves (beams) of sufficiently coherent electromagnetic radiation provides information about the waves and/or their differences.

Theory and Application

In modern manufacturing, interferometry is commonly encountered in:

- Definition, realization, and dissemination of standards of length and form



Interferometry, Fig. 1 Propagation of a wavefront

- Measurement of displacement for the control or calibration of production and measuring machines
- Measurement of the surface form of optics and precision machined metal and other components
- Measurement of surface texture

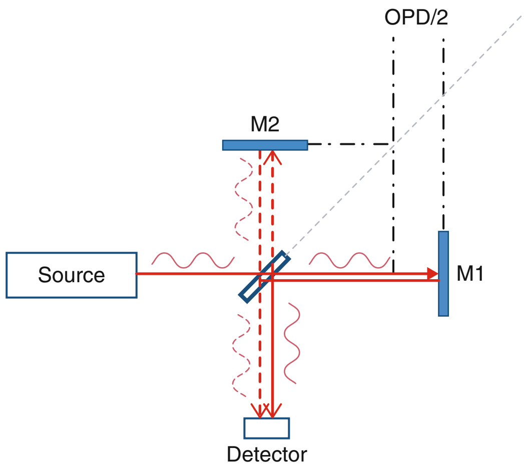
Before considering each of these areas in turn, the fundamentals of interferometry will be very briefly reviewed. Most applications of interferometry in manufacturing use "light" ranging from the UV to the infrared (i.e., wavelengths from ~350 nm to 10.6 mm); in principle everything discussed here applies at any wavelength for which appropriate beam splitters, reflectors, sources, and detectors exist.

Each of the major sections of this article takes the Michelson interferometer as its point of departure. It is, conceptually, an easily understood interferometric configuration and is used to some extent in each of the main areas identified above.

Basic Concepts

The fundamental ideas of interferometry are treated, at various levels of mathematical rigor, in standard optical texts (Hecht 2003; Born et al. 1999). Conceptually, interferometry is most easily understood in terms of the wave nature of light, an electromagnetic wave (following Maxwell's equations) with a phase that changes by 2π radians every wavelength. A wavefront is a surface of constant phase (e.g., the peak, valley, or any other phase in Fig. 1).

The Michelson is a conceptually simple interferometer (Fig. 2). Collimated light from



Interferometry, Fig. 2 Michelson interferometer

a source is divided into two beams, each of which reflects off mirrors and returns through the beam splitter to a light-sensitive detector. The time-averaged intensity depends on the phase difference between the two beams. If the path lengths of the two beams is equal (modulo 2π), the waves interfere constructively (intensity increases); minimum intensity is observed when the beams are exactly out of phase (destructive interference). As the optical path difference (OPD) varies, the detected intensity (phase) varies.

The Michelson is a common form of interferometer in production engineering applications. Like most interferometer configurations, it splits the amplitude from the light source. A more limited number of interferometer configurations use wavefront division (see, e.g., Hecht 2003).

Two other critical factors need to be considered: coherence and polarization. The range of OPDs over which visible fringes, or interference with reasonable contrast, occur can be described by the "coherence length" of the source. From the perspective of a thermal source, this can be derived from the time over which a single frequency wave is emitted and the speed of light. Alternatively coherence length (l_c) can be approximated (Young 2000) for a source with a center wavelength λ emitting over a finite bandwidth (Δλ) from:

$$l_c = \lambda^2/\Delta\lambda$$

The linewidth of an unstabilized HeNe laser is approximately 1 ppm, leading to a coherence length of order 0.5 km. For conventional thermal sources (such as a tungsten filament bulb) or a diode, the coherence length is a small number of micrometers. As will be seen below, both long and short-coherence sources are used to good effect in different interferometric tools commonly used in production engineering.

Interference also requires that the two beams have the same polarization. In interferometric systems using long coherence sources, use of appropriate quarter- and half-wave plates and polarizing beam splitters enable multi-pass configurations for displacement measuring interferometers and increased photon efficiency in instruments for the measurement of surface form.

The visibility (or contrast) of the fringes detected depends, in addition, on a number of factors including the relative intensities of the two beams, incoherent background light within the bandpass of the detection system, and coherent scattered light.

Realization and Dissemination of the Unit

In 1875, the Convention du Metre defined the unit in terms of engraved lines on a platinum-iridium artifact stored at the Bureau International des Poids et Mesures (BIPM) at Sèvres on the outskirts of Paris; practical realizations required comparison of artifacts with "the meter." In 1892–1893 Michelson and Benoit made the first measurement of the meter by comparison to a cadmium emission line. Dissemination of the unit, however, was, by a chain of intercomparisons of length standards, ultimately traceable to the artifact at BIPM, using increasingly sophisticated optomechanical comparators (Evans 1989). For many decades, National Measurement Institutes (NMI) such as NIST, NPL, and PTB have used multiwavelength interferometry for calibration of gage blocks.

The need for a documented chain of intercomparisons in order to provide a "traceable" measurement of length was eliminated in 1960 by the redefinition of the meter in terms of the radiation from a defined krypton source. The meter was redefined in 1983 as the length of the path travelled by light in vacuum in $1/c$ seconds (where c is the speed of light). In conjunction with CIPM recommended radiations and their associated wavelength uncertainties (listed on the BIPM website), this means that the meter can be practically realized using a displacement measuring interferometer without reference to an NMI and, given an appropriate uncertainty analysis, measurements made with such a system are traceable according to the requirements of ISO 17025.

In 2007 CIPM added an unstabilized HeNe laser to the list of recommended radiations with a relative standard uncertainty in the vacuum wavelength of 1.5 ppm (Stone et al. 2009).

Displacement Measuring Interferometry

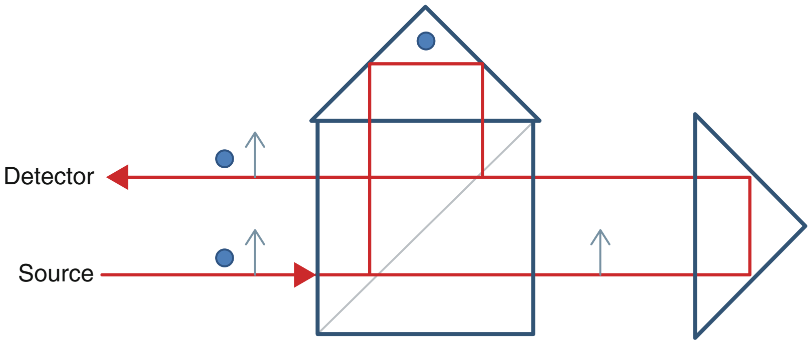
The Michelson interferometer described above is the basic configuration for the vast majority of commercially available systems used for:

- Measurement and control of the position in a variety of state-of-the-art manufacturing equipments
- Calibration of the six degree-of-freedom errors in positioning of systems such as machine tools and coordinate measuring machines

Long coherence sources allow significant differences in the reference and measurement path lengths.

Modern displacement measuring interferometer systems (Badami and de Groot 2013) rarely rely on "fringe counting." Generally,

Interferometry, Fig. 3 Michelson interferometer configuration for displacement measurement



polarization coding of the reference and test beams and their separation and recombination at a polarizing beam splitter (Fig. 3) allow automated computation of phase and direction of motion. Systems optimized for a small number of axes commonly rely on homodyne detection. For large numbers of axes (e.g., ~30 axes have been used in lithography tools for integrated circuit manufacturing), heterodyne systems have advantages.

In a homodyne detection scheme, the return beam is divided and additional phase shifts imposed by appropriate polarization optics (e.g., quarter- and half-wave plates), giving at least three phase shifts between them. Intensities at multiple detectors are combined to give phase (OPD) at nanometer resolution.

In the heterodyne method, there is frequency offset between test and reference beams, given for example, by an acousto-optical modulator in the source. The frequency of the intensity fluctuations when test and reference beams are recombined depends on the relative direction and velocity of motion. With appropriate data processing, sub-nm position resolution and tens of kHz bandwidth can be obtained.

As noted above, single-axis displacement measuring interferometers have been used for measurement and control of the linear axes of grating ruling engines, high-precision machine tools (Donaldson and Patterson 1983), and coordinate measuring machines, including metrological AFMs and line scale comparators. Plane mirror interferometers are used on such machines when, for example, straightness measurement and correction is required. Integrated circuit manufacturing applications (especially lithography systems) typically use two-axis stages with all degrees of freedom measured and controlled. A variety of high-stability plane measuring and angle measuring interferometer configurations are used.

Displacement measuring interferometers provide the means for external calibration of many machines, for example, following ISO 230-6. Other approaches include the use of laser tracers or laser ball bars implementing trilateration to measure machine error motions.

Displacement measuring interferometry, especially where laser sources are used, offers high-resolution, high-bandwidth metrology over large dynamic ranges. Measurement uncertainty depends on a number of sources, most commonly:

- Environmental index variation: The measured OPD depends directly on the refractive index of the medium through which the wavefront propagates. Turbulence adds "noise," while uncertainty in the air temperature, pressure, and composition (particularly hydrocarbons) adds a time invariant component to the uncertainty. Addition of a "wavelength tracker" can reduce the effect of errors that are uniform across the paths of tracker and measurement axes.
- Thermal effects: The variation of air index with temperature (dn/dT) is small compared to the coefficient of thermal expansion (α) of common materials for machine or metrology frame construction, except Zerodur, Invar, and similar "exotic" materials. Displacement measuring interferometry commonly involves

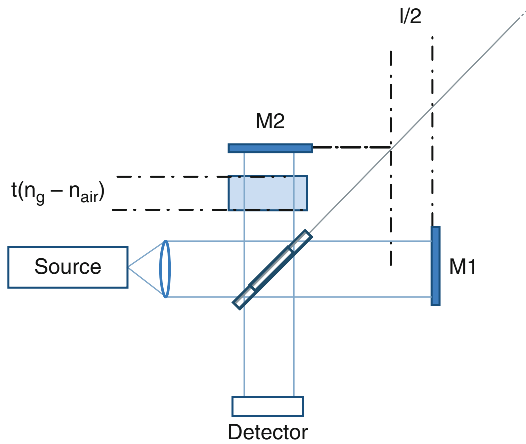
monolithic beam splitter and other optical components for which α and dn/dT are significant.

- Setup errors: Uncertainty in the alignment of optical and mechanical axes adds a cosine error to the uncertainty (single sided) and Abbe offsets convolve with angular error motions of slides to give uncertainties that vary with position.
- Source wavelength: The wavelength uncertainty of unstabilized HeNe lasers (∼1.5 ppm) is rarely sufficient for precision machine applications. Commercially available stabilized lasers for metrological applications typically offer short-term stability in the vacuum wavelength of a few parts per billion, although the traceability of the wavelength is typically less well known. Integration of an iodine-stabilized reference source offers the possibility of combining the short-term stability and functionality of a commercial metrological laser with uncertainty in the realization of the unit to parts in 10^{11}.
- Beam shear: Over large OPDs, or in critical applications, imperfections in the wavefronts convolved with misalignment of test and reference beams can introduce errors proportional to the wavefront shear.

Note that there is a multiparameter trade-off between grating-based (interferometric) evaluation of displacement and direct interferometric evaluation. Typical grating-based systems have relatively short non-common paths, resulting in reduced sensitivity to time-varying index effects. There is, however, increased sensitivity to cyclic effects in grating production and long-range effects of coefficient of thermal expansion. A detailed discussion of this trade-off is beyond the scope of this article.

Interferometric Measurement of Form

Consider again Fig. 2, replacing the “rays” with wavefronts of finite extent and the point detector with an area-sensitive detector such as a screen or charge-coupled device (CCD). The Michelson interferometer has now been converted (Fig. 4) into a Twyman-Green interferometer (patented in

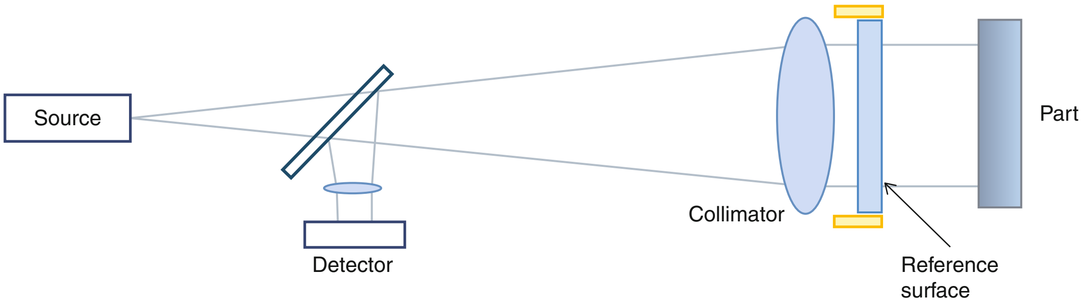


Interferometry, Fig. 4 Twyman-Green interferometer

1916) useful for the comparison of wavefronts such as those transmitted through (Fig. 4) or reflected from optical components including lenses, prisms, and windows. If the OPD through a component under test in transmission (the product of thickness and index difference) is equal to the difference in path lengths for test and reference beams (l/2), then high-contrast interference fringes will be observed even for the short coherence sources available in 1916. This fringe pattern shows the difference between test and reference wavefronts.

The block of glass (specified by $t(n_g - n_{air})$) in Fig. 4 can be replaced by beam shaping optics and a surface or system under test. More significantly, the source can be replaced by a laser (long coherence) source and the optical configuration converted to a Fizeau (Fig. 5), in which the reference surface also acts as the beam splitter. This means that the optics to the left of the reference surface are essentially “common path” to reference and test wavefronts, and hence, their errors cancel out in the measurement.

Figure 5 shows the Fizeau interferometer with a flat reference surface testing the front surface of flat part. Transmissive windows can be tested, as in the Twyman-Green (Fig. 4). The reference flat can be replaced with a system of beam shaping optics including a final curved reference surface. In this configuration, the Fizeau can be used to test a curved surface whose center of curvature is



Interferometry, Fig. 5 Fizeau interferometer

at the center of curvature of the reference surface (the confocal position).

A variety of other test configurations are possible (Dörband et al. 2012) including:

- Measurement of radius of curvature by measuring displacement as the object is moved from confocal to the cat's eye position (where a converging beam is retroreflected from the curved surface
- Measurement of surfaces with systematic departures from spherical (aspheres), provided that the departure is small enough that the fringe pattern does not exceed the dynamic range of the instrument ("mild" aspheres)
- Measurement of higher departure aspheres using beam conditioning optics (nulls) which may be diffractive, refractive, or reflective
- Measurement of conics (parabola, ellipsoids, etc.) in double-pass configurations
- Measurement of retroreflectors and prisms

Fizeau interferometers have been available commercially for approximately 40 years and have been sold at operating wavelengths from 248 nm to 10.6 μm, although the vast majority operate at 633 nm. Initially, the fringe patterns were interpreted visually or by fitting fringe centers. This limits achievable resolution and requires that the sign of the local slope be separately identified.

One solution (Takeda et al. 1993) is to add a tilt of known direction, so that the fringe pattern is dominantly a set of parallel lines with the departure from nominal shape encoded as small variations from that. If the intensity data can be processed in the frequency domain, the "carrier" can be subtracted and the residual, its sign now known, evaluated.

Another approach mounts either the part or, more commonly, the reference optics on a mechanical translator (shown in yellow in Fig. 5) so that intensity frames can be acquired at a number of intervals (Bruning et al. 1974), typically uniformly spaced by $\lambda/4$. This method, phase shifting, uses multiple intensity frames (minimum 3, typically 7 or more in modern instruments) to solve for the phase modulo 2π at every pixel. Departure of the combined wavefront from its nominal shape over the aperture can be "unwrapped" provided adjacent pixels have a phase difference less than 2π.

Dominant sources of uncertainty in measurements of flats and spherical surfaces in Fizeau interferometry are:

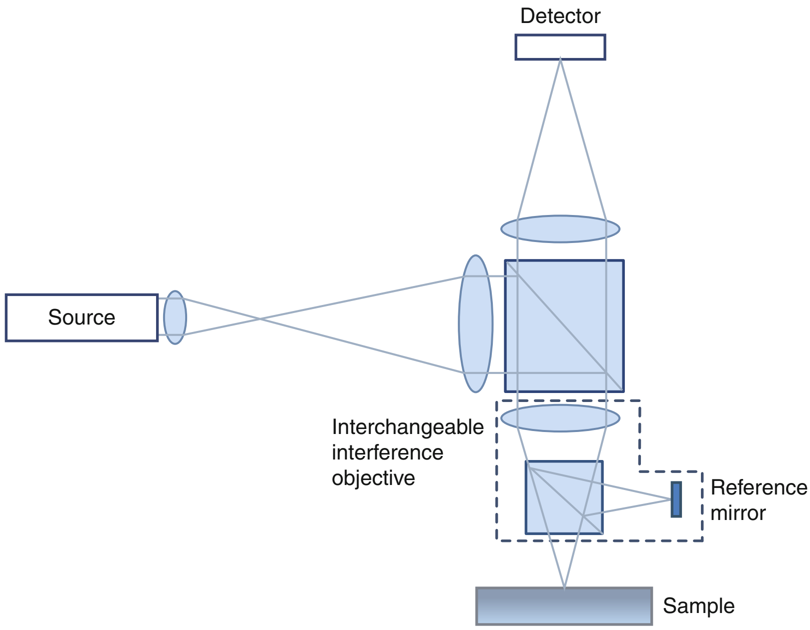
- Knowledge of the shape of the reference surface
- Mounting stresses
- Environmental, including variation of the index of refraction of air in the test cavity, vibration, and thermally induced changes of the shape of reference and test optics

In measuring aspheres, additional sources of uncertainty include:

- Knowledge of the null optics and their exact position
- Distortion of the coordinate system
- Effect of operating in a non-common path configuration

Flats, spheres, and aspheres for lithography applications have been measured to sub-nm

Interferometry, Fig. 6 Schematic of a microscope set up with a Michelson interference objective



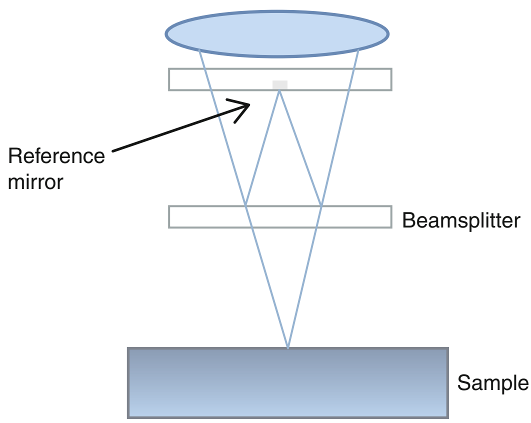
uncertainties using Fizeau interferometers. Next-generation telescope primary mirrors with apertures up to 8 m are also being measured with Fizeaus.

Surface Roughness

Twyman-Green interferometers can be constructed with small test beam apertures (less than 2 mm) and imaging performance that allow measurement surface structures on smooth surfaces. A more convenient approach is to use an interference objective, for example, a Michelson (Fig. 6) or Mirau objective (Fig. 7) on a microscope, providing height information at the lateral resolution of the microscope system. Objectives at a variety of magnifications can be turret mounted and provided with a mechanical translation. For smooth surfaces (where the phase change between pixels is less than 2π), the phase-shifting methods discussed above can be implemented directly (de Groot 2011a).

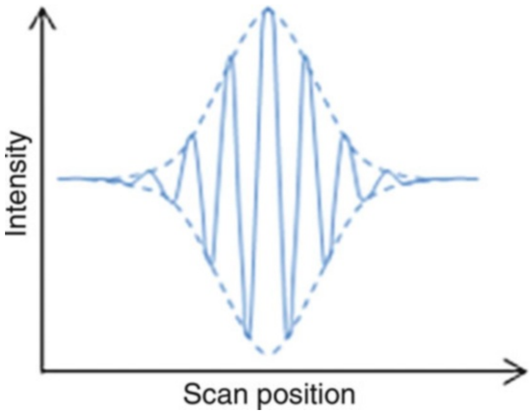
The Michelson objective works well for low NA, low magnification objectives with a large depth of focus. At higher magnifications, the beam splitter in the objective becomes impractical. Figure 7 shows, schematically, a Mirau objective.

For a broadband (white light) source, interference is observed over a short range of translation of the objective. Figure 8 shows, schematically,



Interferometry, Fig. 7 Mirau interference objective

the intensity modulation as a function of scan position for a single pixel. This modulation can be analyzed at each pixel of a detector independently to provide a height map. This method, known as Scanning White Light Interferometry (SWLI) or Coherence Scanning Interferometry (CSI), can provide measurements of both smooth and rough surfaces, as well as step heights and film thicknesses (de Groot 2011b). Custom microscope objectives can be designed for measurement of features such as the interior of small bores.



Interferometry, Fig. 8 Intensity as a function of scan position (*solid line*) and modulation envelope

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Internal Logistics

▶ Material Flow

Interpolation

▶ Computer Numerical Control

Ion Beam Etching

▶ Ion Beam Machining

Ion Beam Machining

Fengzhou Fang and Zongwei Xu
College of Precision Instruments and Opto-electronics Engineering, Tianjin University, Tianjin, China

Synonyms

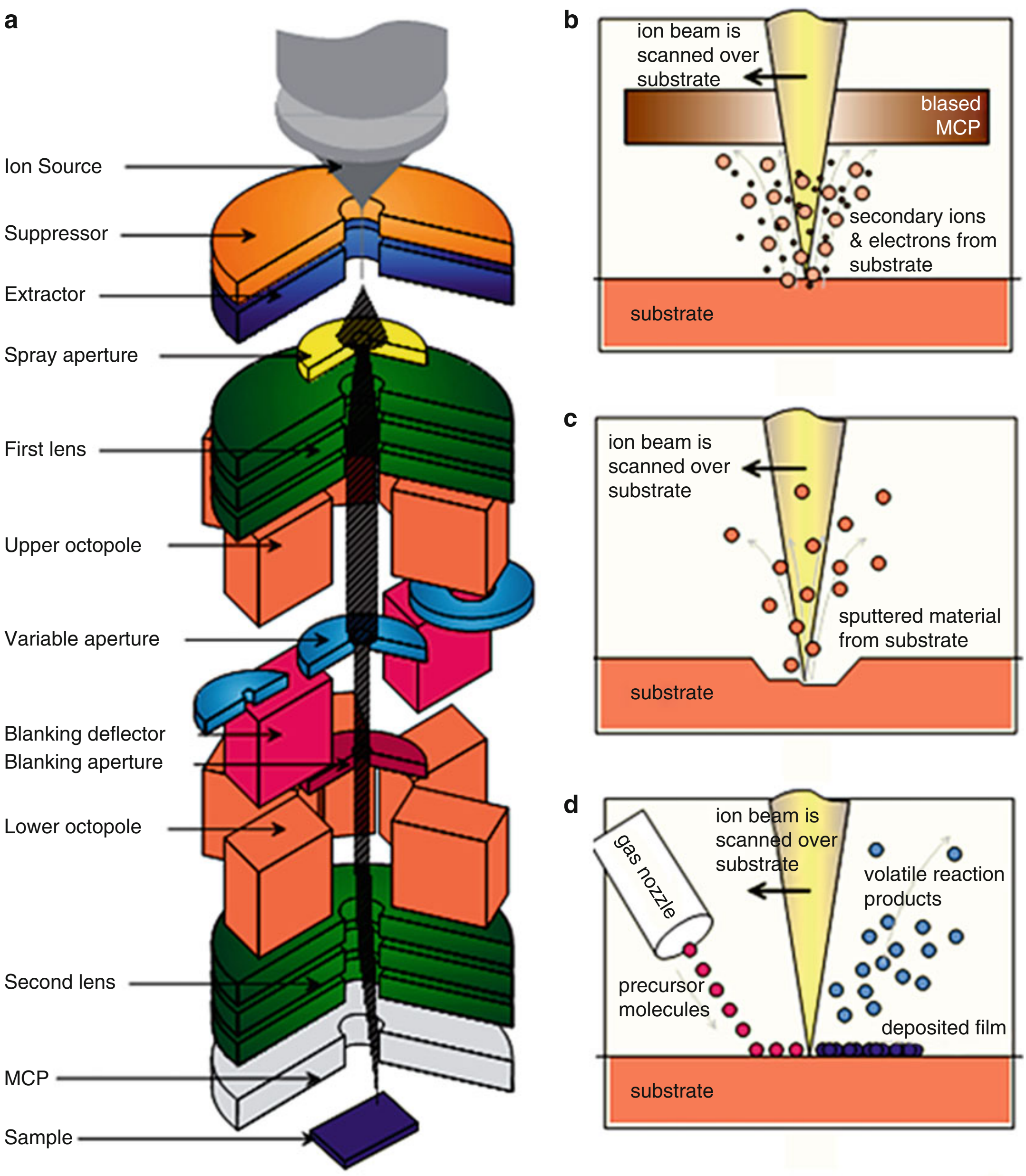
Ion beam etching; Ion beam smoothing

Definition

Ion beam machining is an important nonconventional manufacturing technology used in Micro/Nanofabrication, using a stream of accelerated ions to remove the atoms on the surface of the object.

Theory and Application

Ion Beams Machining (IBM) is an important nonconventional manufacturing technology (Hellborg et al. 2009), which uses a stream of accelerated ions by electrical means in a vacuum to remove, add, or modify atoms on the surface of the object. IBM can be classified into two main categories, that is, Large-area Ion Beam Machining (LIBM) technology and Focused Ion Beam Machining (FIBM) technology (Fig. 1).



Ion Beam Machining, Fig. 1 Schematic diagram of a Focused Ion Beam (FIB) ion column (**a**), work principle of FIB imaging (**b**) FIB milling (**c**) and FIB induced deposition (**d**) (Reyntjens and Puers 2001)

Types of Ion Beam Machining and its application are described as follows.

Large-Area Ion Beam Machining (LIBM)

Ion Beam Figuring (IBF)

Introduction IBF is one kind of Ion beam machining accomplished through scanning an ion beam with high ion energies as high as 300 keV across the workpiece with appropriate computed velocities by accurately controlling the beam dwell time. IBF is a deterministic method, which does not require to contact the substrate when performed and allows for figuring complex shapes.

Application IBF technique has been developed for figuring high performance optics components, such as high precision optics used within the optical towers of lithography wafer steppers. Following other mechanical polishing methods, IBF is usually performed as the final step to remove the last surface errors.

Ion Beam Smoothing (IBS)

Introduction IBS has the similar process of IBF using lower energy beams, typically less than 2 keV.

Application IBS has been successfully employed to fabricate ultrasmooth surfaces with rms roughness values of 0.2 nm (Allen et al. 2009).

Reactive-Ion Etching (RIE)

Introduction Reactive-ion etching (RIE) is an important ion beam etching technology used in microfabrication. A plasma is struck in the gas mixture using a radio frequency (RF) power source, breaking the gas molecules into ions. The accelerated ions not only react at the surface of the material being etched (forming another gaseous material), but can also sputter some material by transferring their kinetic energy. Many process parameters, such as gas flows and RF power, would greatly influence the RIE results.

Application As a special subclass of RIE, Deep RIE (DRIE) has been widely adopted by the MEMS community. The sidewalls of the DRIE etched structures are nearly vertical and the depth can be hundreds of microns into the silicon substrate.

Ion Beam Implantation

Introduction Ion implantation is one of the important materials engineering processes, where ions are accelerated in an electrical field and implanted into the substrate.

Application In order to change the physical, chemical, or electrical properties of the solid substrate, ion implantation technique has been widely used in semiconductor device manufacturing and in metal finishing, for example, semiconductor doping, silicon on insulator (SOI) substrates preparation, and steel toughening.

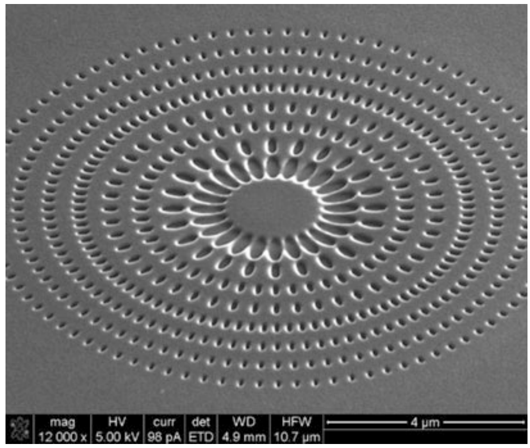
Focused Ion Beam Machining (FIBM)

Compared with the Large-Area Ion Beam Machining process, the ion beams in the Focused Ion Beam (FIB) process are focused to produce a beam of a smaller diameter. FIB can be considered as a compound platform combining a cutting tool possessing a beam diameter of tens of nanometers with a nanometer's imaging resolution microscope. Moreover, uniquely, FIB is capable not only of milling substrate materials, but also adding materials at predefined locations with high resolutions. Versatile materials, such as diamond, metal, thin film, polymer, and glass, can be processed by FIB. In FIB system, the ion beam ionized and emitted from liquid-metal ion sources (LMIS), is accelerated, collimated, focused, and finally injected into the target with energies from several to dozens of kilo-electronvolts. Then, a cascade collision occurs, in which energy and momentum are transferred from the incident ion to the target. These collisions result in a series of effects which mainly include: displacement of atoms and ion deposition in the sample (induced damage and ion implantation), sputtering of neutral and ionized substrate atoms (an effect realizing substrate milling), electron emission (an effect realizing imaging), and chemical interactions of breaking chemical bonds and thereby dissociating molecules (this effect is exploited in the ion-induced deposition) (Reyntjens and Puers 2001). FIBM technology mainly involves three major approaches: FIB milling or sputtering, FIB-induced deposition (FIBID), and FIB implantation (FIBI).

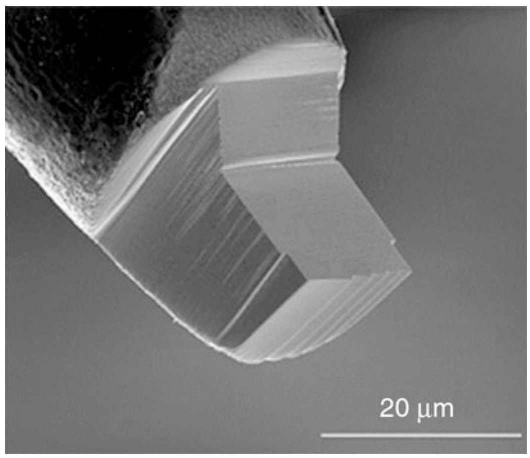
FIB Milling

Introduction FIB milling, also called FIB direct writing (FIBDW), has been widely applied in the micro/nanomanufacturing fields. The key issue in the FIBDW is to operate an FIB with proper process parameters, such as ion beam size, beam shape, beam overlap, and dwell time, for removing a specified volume of material from a predefined localized area. The ion channeling effect might degrade the fabricated surface's smoothness if the target material is a crystalline material, the incident ions may penetrate much deeper along the low indexed axis of crystalline.

Application FIBDW finds wide applications in the nanopatterning for nano-optics, bio-sensing, and nanomanufacturing. Micro cutting tools with nanometric cutting edges and complicated shapes can be fabricated by controlling the tool facet's orientation relative to the FIB (Figs. 2 and 3).



Ion Beam Machining, Fig. 2 Pinhole array fabrication result by FIBDW using in the nano-optics



Ion Beam Machining, Fig. 3 Micro cutting tool shaped by focused ion beam direct writing (Zhang et al. 2009)

FIB-Induced Deposition (FIBID)

Introduction FIBID can be employed to realize the localized maskless deposition of both metal and insulator materials. In the FIBID process, the precursor gas is first sprayed and then adsorbed locally on the sample surface using a fine nozzle. The injecting ion beam decomposes the adsorbed precursor gases. The desired reaction products would be fixed on the surface and form a thin film.

Application FIBID can be used as a flexible adhesive in the micro/nanodevices' fabrications. For example, a carbon nanotube (CNT) can be fixed to the end of an ordinary probe of atomic force microscope by the FIBID process combining with the nanomanipulations.

FIB Implantation (FIBI)

FIBI has been studied in the etching mask, nanoholes fabrication, and 3D nanostructures fabrication. The FIBI layer could be used as etching mask in the microfabrication; based on that the etching rate of FIB irradiated area is much lower than that of nonirradiated area during the subsequent dry (wet) chemical etching or subsequent in situ FIB XeF2 gas-assisted etching.

Simulation Tool for FIB

Stopping and Range of Ions in Matter (SRIM), a group of computer programs which calculates the interaction of ions with matter (Ziegler 2004), has been widely adopted in the IBM researches. As a core program of SRIM, the Transport of Ions in Matter (TRIM) program involves a Monte-Carlo calculation which follows the ion into the target with about 10 eV $\sim$ 2 GeV ion energy, making detailed calculations of the energy transferred to every target atom collision. TRIM can be employed to calculate both the ions' final 3D distribution and all the kinetic phenomena associated with the ion's energy loss such as target damage, sputtering, ionization, and phonon production.

Key Applications of IBM

IBM has become one of the key approaches in micro/nanofabrications for various applications, such as nano-optics, MEMS, and nanomanufacturing.

Cross-References

▶ Resolution
▶ Sensor (Machines)

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Ion Beam Smoothing

▶ Ion Beam Machining

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