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New manufacturing techniques for new engine component designs

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Abstract

Over the last few years, significant progress has been made in the field of manufacturing technology. New or improved manufacturing techniques, such as additive manufacturing, PECM (precise electrochemical machining), IHFP (inductive high-frequency pressure welding) or multi-axis electro-discharge machining, help overcome existing manufacturing constraints and develop new component designs. Such new designs are characterized by their higher functionality, i.e. one component serves multiple functions. Moreover, they require fewer manufacturing operations, which markedly reduces costs.

The paper describes the basis of selected examples, the progress in manufacturing technology and its impact on design and efficiency

Subscripts

ACARE	Advisory Council for Aero-Nautical Research in Europe
blisk	Bladed disk
IBR	Integrated bladed rotor
EDM	Electro-discharge machining
IHFP	Inductive high-frequency pressure welding
PECM	Precise electro-chemical machining
HCF	High cycle fatigue
LCF	Low cycle fatigue

Motivation

In the past, new designs aiming the efficiency of engines at markedly reduced emissions and the consumption of resources - in line with the ACARE targets - were frequently limited by manufacturing constraints.

Typical examples of the targets defined in the 2020 Vision:
Reduction of CO_2 emissions by 50%
Reduction of NOx emissions by 80%
Reduction of perceived noise by 50%

New materials capable of withstanding even higher temperatures such as powder metallurgically produced superalloys, as well as new component designs, such as blisks / IBR’s, thin-walled structures and disks, needs advanced manufacturing technologies.
New approaches in processing technology, in machinery, fixturings and tools, but also in inspection and measuring techniques have helped to overcome or at least lessen many of the manufacturing constraints.
With respect to the future there are more advances in manufacturing engineering to open up entirely new possibilities for the design of highly integrated components which enable to further boost engine efficiency.

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Examples of manufacturing processes which open up new possibilities in engine construction are:

1) Additive manufacturing processes
2) Multi-axis electro-discharge machining
3) Process control of machining methods (adaptive machining)
4) New tools, such as internally cooled grinding wheels
5) IHFP (inductive high-frequency pressure welding)
6)PECM (precise electrochemical machining)
7) Cold spraying
8) Superfinishing of aerodynamic profiles by polishing
9) Roller burnishing
0) New methods for determining the residual stress depth profiles on engine-run components

Improvement potentials in engine construction

The design of engines is still strongly influenced by the limited possibilities offered by a rather conservative manufacturing engineering approach. So far new manufacturing technologies are necessary.
In addition, new manufacturing processes are expected to make major contribution towards reducing manufacturing costs, improving process stability and increasing the service life of components.
The table below lists key components for future engine generations and their influence on performance data. In addition, the enabling core manufacturing processes are listed as well.

Key components for future generations of engines and their impact on performance

	Blisk	**Casing treatment**	**Coatings**	**Sealing systems (brush)**	**Integral designs**	**Surface quality / structure**	**Thin walls**	**Complex geometries**	**Composite materials**
	Fan, LPC, HPC, LPT	HPC case	Engine	Engine	Engine	HPC	Engine	Engine	Engine
Efficiency	X	X	X	X		X		X	
Power density	X						X		
Weight	X	X			X		X		X
Lifetime			X	X				X	
Reliability			X			(X)		X	X
Operability									X
Secondary loss				X	X				
Cost				X	X				
Substitution for	Disk - blade	Variable guide vanes	Upgraded materials	Seals / honeycombs	Individual components				
Function / Components		Surge margin improvement, stabilization, partial load	Rub-in system, erosion, corrosion, oxidation protection	Sealing					Dual blisk for compressor, turbine
Advanced manufacturing prozesses	Joining, milling, PECM	Milling, additive manufacturing	Cold spray, HVOF, Plasma spraying electroplating, painting	Wind, crop	Additive manufacturing	Ultra-polishing, asymmetrical leading edge, PECM / Laser structuring	Blade profiles, disks, casings	Blades / vanes with dihydral geometry	IHFP, Adaptive milling

The introduction of new or substantially improved manufacturing processes offers the chance:

1. to produce existing components at a higher quality, at lower costs and enhanced process stability,
2. to substitute existing processes and process chains, and
3. to produce "new highly integrated components" with markedly improved properties as well as components that combine the properties of several conventionally produced components.

This will not be accomplished at once, but in progressive stages.

In the following, examples of the options available will be presented.

Examples of improvements

Roller burnishing

Figure 1: Roller burnishing

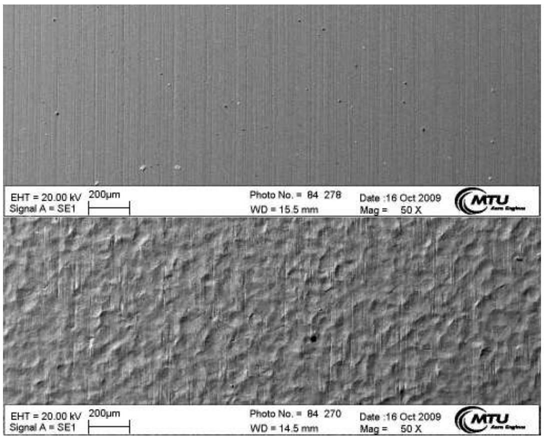


Figure 2: Comparison of roller-burnished (top) and shot-peened (bottom) surfaces

Roller burnishing is a method of work-hardening the surfaces of metallic components. The tool used is a hardened sphere that is hydraulically pressed onto the surface to selectively induce compressive residual stresses As can be seen from figure 2, roller burnishing results in a markedly improved surface finish as compared with the ground or conventionally shot-peened condition.

The roller burnishing marks are overlapping so that a homogeneous residual stress distribution is obtained in the component. This results in an increased strength, longer HCF- and LCF-live and in reduced notch sensitivity.
For airfoils, an additional benefit is, that higher strength and improved surface finish (Rz<1) help to increase the efficiency.

Adaptive processes for turning of thin-walled components

Thin-walled components tend to vibrate during turning. This results in a poorer surface quality and in increased tool wear. In some cases, even tool fracture may occur. New approaches aimed at adaptively controlling the turning parameters permit even minor vibrations to be detected by means of sensors. These vibrations can then be dampened by appropriate parameter changes so that there is no need for costly fixturing for vibration damping.
In the process, the parameters are varied within a very small range only. These variations are validated by comprehensive testing within the framework of qualification and approval.
Figure 3 shows the surface of a thin-walled disk turned without and with adaptive control of the parameters.
Adaptive control of machining processes permits weight-reduced compressor and turbine disks to be manufactured in a highly efficient manner.

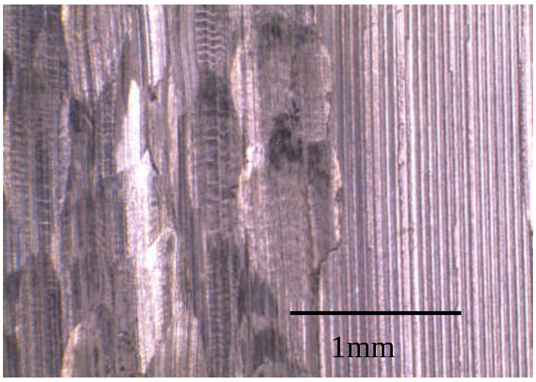


Figure 3: Turned surface of a thin-walled disk
Left side: Surface turned without adaptive control
Right side: Surfaces turned with adaptive control.

Internally cooled grinding wheels for the cost-effective manufacture of thin-walled structural components.

An engine contains many thin-walled structural components, such as shrouds, fairings and panels, which feature thin-walled and frequently also curved webs, retaining hooks or deep grooves that must be produced cost-effectively by grinding. A major problem in the process is an adequate supply of coolant-lubricant for multi-axis grinding operations where the spindle moves around during grinding and where the grinding wheels can be changed automatically. A possible solution to this problem are grinding wheels with internal cooling canals which are manufactured using additive processes and provided with a layer of CBN particles.

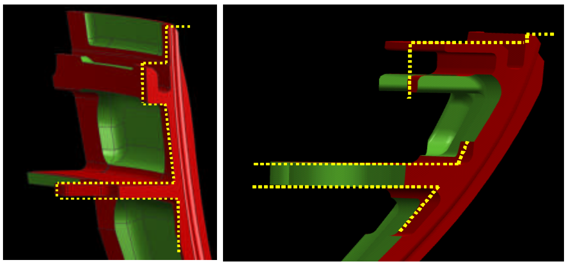


Figure 4: Examples of thin-walled ground contours

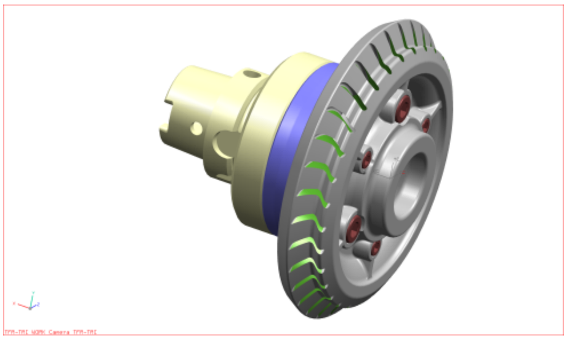


Figure 5: CAD image of an internally cooled grinding wheel

Such internally cooled grinding wheels permit thin-walled webs, hooks and deep grooves – also with curved contours – to be ground "cold" and hence in a cost-effective manner.

Superfinishing of aerodynamic surfaces

Studies by NASA verify that the efficiency of compressors can be improved if the airfoil surfaces are polished.

Figure 6: Polished blisk and enlarged detail of showing the airfoils

This applies in particular to compressor areas where high Reynolds numbers prevail. To obtain sufficiently smooth surfaces, the airfoils must be post-processed after mechanical or electrochemical machining. The polishing processes available for the purpose include vibratory tumbling, chemically-assisted vibratory tumbling or abrasive flow machining. When selecting the process, care must be taken to make sure it affects the geometry of the aerodynamic profiles as little as possible. Figure 6 shows a polished blisk (Rz<1 µm).

Feasible alternatives to polishing are painting techniques, roller burnishing or precise electrochemical machining (PECM) with smooth parameters. All of these finishing processes are capable of markedly reducing the surface roughness down to Rz values <1µm. This substantially enhances the efficiency of compressors.

Examples of substitutes

ECM/PECM - (precise) electrochemical machining)

PECM is a further development of electrochemical machining. The process is characterized by a markedly smaller gap between component and electrode which substantially enhances the dimensional accuracy of the contour thus produced and improves the surface finish. PECM works without noticeable electrode wear. A major advantage afforded by the process is that the thin-walled profiles cannot be deformed by machining forces, as the only force acting on the airfoils during PECM is the electrolyte pressure.
When machining high-pressure compressor airfoils in nickel alloys tool wear increases with increasing high-temperature resistance of the alloy. Tool wear is particularly high with powder metallurgically produced materials. For these materials, tool costs may be the most important item on the blade production bill.
With PECM, powder metallurgical (PM) materials can be machined faster than forged alloys. Reproducibility is excellent and electrode wear negligible.

Normally, conventional electrochemical machining is the process used for rough-machining to precontour the blisk airfoils. The final contour is then produced by precise electrochemical machining.

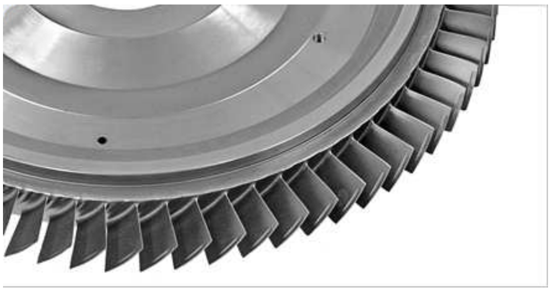


Figure 7: Blisk airfoils produced by PECM

This sequence of ECM and PECM is a suitable process chain for blisk airfoils – including those with pronounced 3D contours - in PM nickel alloys which are extremely difficult to machine using conventional processes. Furthermore, PECM can be used also to cost-effectively machine γ-Ti blades.

If suitably profiled electrodes are used aerodynamic structures intended to influence the airflow can be produced in only single operation along with the airfoil contours.

Cold Spraying

Cold spraying is a new process to produce coatings that are characterized by excellent properties in terms of freedom from oxides, very low porosity and high adhesive strength. The thermal stresses induced in the process are low. In addition, cold spraying stands out by its high deposition efficiency (>60%) and short spraying times.

Since, as a result of the low thermal stresses and the high particle speed, compressive stresses are produced in the coating, the process is suitable also for deposition of very thick coatings.

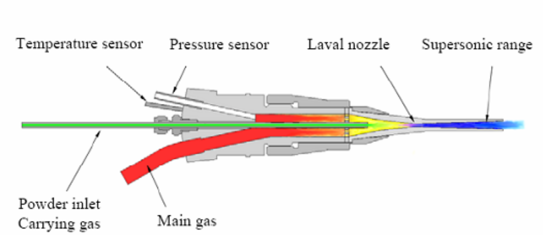


Figure 8: Cold spraying system

Procedural principle:

- Acceleration of highly compressed and hot nitrogen through a Laval nozzle
- Axial injection of spraying powder
- The powder particles hit the component to be coated in unmolten condition and with a very high kinetic energy and are "forged" into the surface.
- Ductile materials are used exclusively as cold spraying materials.

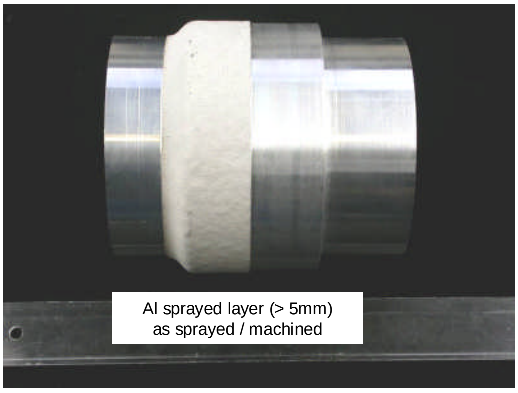


Figure 9: Component with thick Al coating > 5 mm

The process lends itself also for the additive production of component contours, mainly in the repair of components. It moreover offers the possibility of producing composite materials to be able to optimally meet local component requirements by combining different materials.

IHFP (inductive high-frequency pressure welding)

IHFP is a highly efficient pressure process for joining materials. In the process, the fusion zone is uniformly heated by means of an induced current. After approximately 4 seconds the joining temperature (≤ melting temperature) is reached and the components are joined under pressure. For titanium components, the joining pressure is between 30 and 40 MPa, for nickel alloy components up to 100 MPa. The joining pressure is maintained throughout the cooling phase.

The welded joint is very homogeneous and the heat affected zone very narrow.

The process can also be used to join different materials, for example, to produce dual-material blisks where blades and disk are made from those alloys that are optimally suited to withstand the stresses occurring in operation.

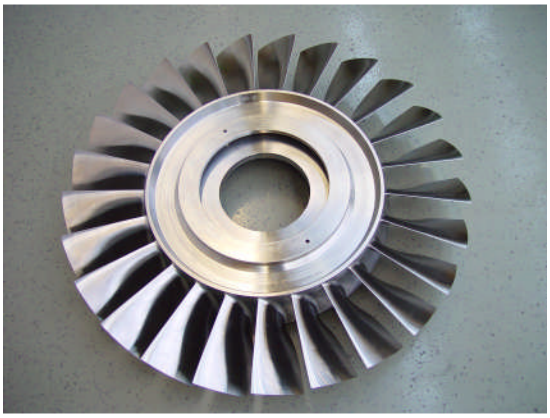


Figure 10: Test blisk consisting of welded-on airfoils in Ti 6242 and a hub in Ti 6246

Inductive high-frequency pressure welding reduces the material demand for LPC blisks and fans by approximately 30%. At the same time, the mechanical properties are improved. The process can be used to produce new blisks and to replace damaged airfoils on engine-run blisks.

In the medium term, IHFP can partly replace linear friction welding which has more geometric restrictions and is not so cost effectve.

Examples of "new" products

Additive manufacture of integral components for rigs and fixtures

Vane segments with honeycomb seals are engine components that normally have to undergo a complex and time-consuming sequence of manufacturing operations. One of the critical process steps is brazing on of the honeycomb elements.

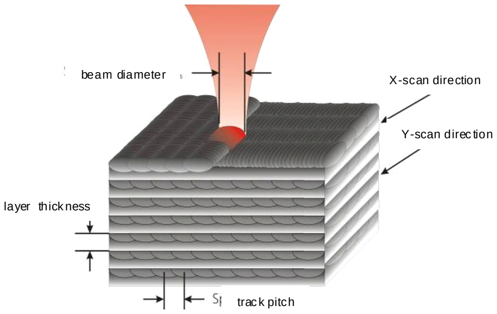


Figure 11: Additive manufacturing technique

Additive manufacturing processes now permit such components to be produced integrally, thus reducing the number of manufacturing steps needed to four: additive manufacturing, heat treatment, smoothening of the surface and machining to produce closely toleranced dimensions. Figure 14 shows a vane segment with integrated honeycomb seals produced by additive manufacturing.

Figure 12: Compressor vane segments with integrated honeycombs (IN718)

The honeycombs can thus be designed more freely as regards their size and shape and their rub-in properties and sealing efficiency can be optimized.

Another example of the use of this technology are coolant-lubricant nozzles for grinding processes.

Figure 13: Coolant-lubricant nozzles for various grinding tasks

Fixture elements, such as nozzles optimized for effective cooling, make a substantial contribution towards stabilizing grinding processes for component contours. Improved cooling helps safely prevent overheating of the material during grinding and increase the material removal rate.

At present, preferred applications for additive manufacturing processes include highly integrated or hollow components and complex structural elements for prototypes and fixtures. Components can be generated directly from the CAD model without the need for a detail drawing. Short manufacturing cycles permit various modifications to be developed and tested.

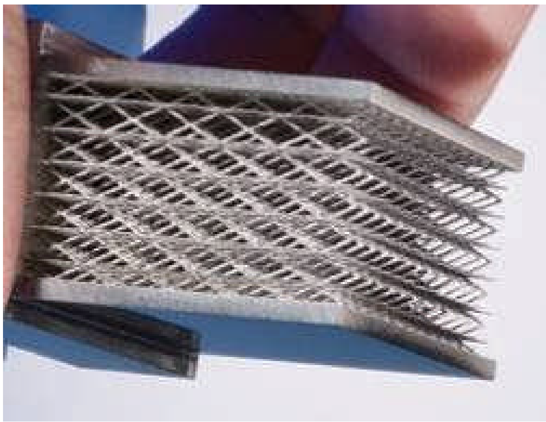


Figure 14: Example for new light weight structure

Non-destructive determination of the work-hardening condition of component surfaces

To increase their service life, rotating engine components are work-hardened to induce residual stresses. The positive effects of such processes are not fully taken into account in the design of these components at present, one of the reasons being the lack of suitable means to measure the work-hardening effects in components, such as disk, non-destructively.
The usual techniques to determine the depth distribution of the work-hardening effects and the residual stresses is the radiographic or hole-drilling method. Both methods destroy the structure. While synchrotron radiation or neutron radiation can be used to determine the depth profiles non-destructively, such method are not cost-effective enough for use in practice.
A new approach towards determination of the work-hardening condition of components by non-destructive means is to make use of the acoustoelastic effect.

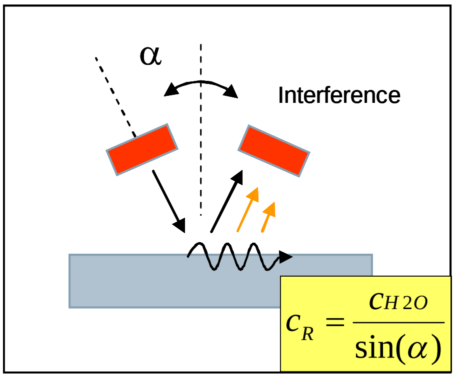


Figure 15: Measurement of the sound propagation velocity c_R, schematic

This approach bases on the fact that the sound propagation velocity in a material depends on the work-hardening condition.
In the process, a highly precise ultrasonic goniometer is used to measure the sound propagation velocity cR of a Rayleigh wave at the critical angle α.

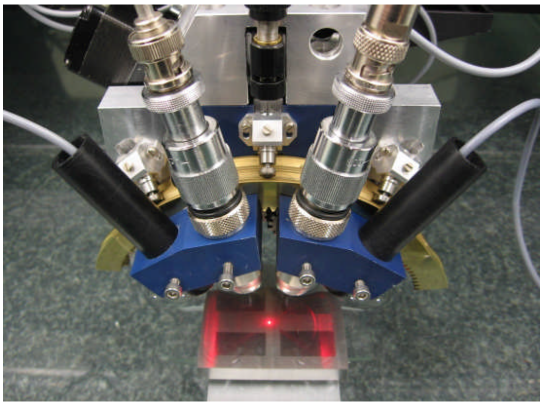
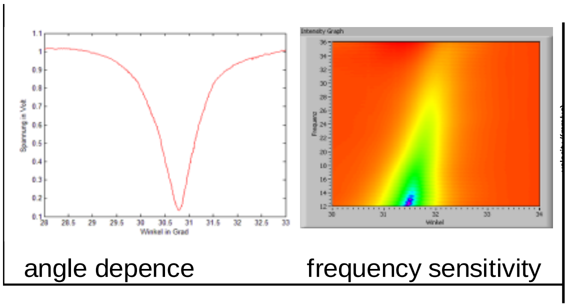


Figure 16: Ultrasonic goniometer for measurement of Rayleigh waves



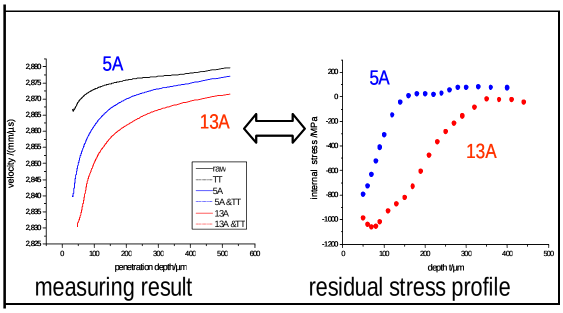


Figure 17: Comparison of first results of ultrasonic measurements of work-hardening/residual stresses and the residual stress distributions determined by radiographic methods

This measuring technique is currently being further refined to make it suitable for use as a non-destructive method of determining the work-hardening condition of component surfaces in an industrial environment.
This new measuring method would then allow work-hardening effects to be taken into account in the component design which would make

it possible to further the reduced the wall thicknesses of components.

Future developments in additive manufacturing

Future engine components will have to satisfy even more stringent requirements in terms of degree of integration, weight/performance ratio and service life. Additive manufacturing processes offer an enormous potential here.
This will afford advantages in cost-effectiveness. The material properties produced by these processes are likely to be superior to those of conventional cast alloys (except for the creep behavior). Moreover, additive processes allow wall thicknesses to be reduced as compared with cast parts and the component complexity to be further increased.

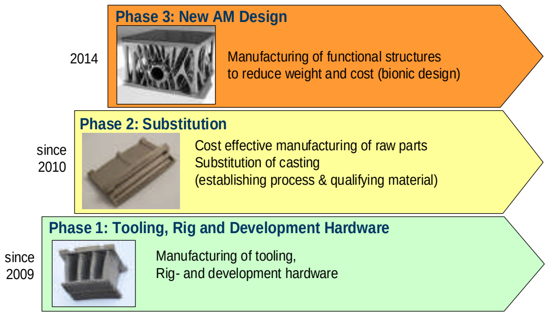


Figure 18: Developments trends in additive manufacturing

Additive processes will, for example, permit designs with bionic structures, and they will enhance the functionalities of components while at the same time reducing their weight.

Possible examples are:

- Vane segments with integrated sensors for pressure and temperature measurement
- Shrouds with internal ducts for air circulation
- Combinations of vane segments and shrouds
- Injection systems with complex air structures like casing treatments, reverse flow systems, cooled airfoils with filigree internal flow systems.

Summary

New manufacturing techniques will help alleviate or even overcome many of the manufacturing constraints that have limited the freedom of design so far. For example, components will be machined using adaptively controlled and hence stable processes which permit components with very thin walls to be produced.
Alternative methods for the production of thin-walled components in alloys that are difficult to machine are electrochemical processes which are characterized by low machining forces. New tool designs will increase the efficiency of machining.
Joining processes, such as IHFP, will help substantially reduce the material volumes required. And new inspection techniques, such as the non-destructive measurement of work-hardening effects, help validate processes.
Additive manufacturing processes will make it possible in the future to design highly integrated components that serve multiple functions at the same time and to manufacture such components in a cost-effective manner.