An Investigation into the Comparative Costs of Additive Manufacture vs. Machine from Solid for Aero Engine Parts

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ABSTRACT

An overview of the relative economics of producing a near net shape by Additive Manufacturing (AM) processes compared with traditional machine from solid processes (MFS) is provided.

A relationship is developed to estimate the specific cost of AM material required to achieve a (typical) 30% saving over conventional MFS techniques. The use of AM techniques are shown to be advantageous for parts which have a high buy:fly ratio, have a complex shape, have a high cost of raw material used for machining from solid, have slow machining rates and are difficult and expensive to machine.

The specific cost of material deposited by additive manufacturing systems required to give a 30% saving over conventional Machine from solid techniques is estimated for a typical aerospace alloy over a range of buy:fly ratios.

The specific costs of a typical aerospace alloy deposited by present and future additive manufacturing systems are estimated and compared with the required specific costs estimated above.

It is concluded that additive manufacture is commercially viable using present additive manufacturing systems for components with a buy:fly ratio of about 12:1. For projected future additive manufacturing systems economic production of components with a buy:fly ratio of about 3 should be feasible.

1.0 INTRODUCTION

1.1 Preamble

In the production of aero engine parts the aerospace industry traditionally takes large ingots of high quality, high cost materials and spends many machine hours at high cost rates on multi million pound machine tools machining away anything up to 98% of the original billet to achieve the desired form.

This approach is seen as being born from a technology led situation and, intuitively, is regarded nowadays as being wasteful in terms of both manufacturing and environmental resources. The immediate future promises a steady increase in raw material costs and increasing pressure from the Environmental Lobby to minimise the generation of greenhouse gases and waste.

As technology progresses and business becomes more competitive the aerospace industry changes more and more to a cost-led situation. The traditional machine from solid (MFS) approach is now being challenged by the concept of 'Additive Manufacturing' (AM) which aims to produce an intermediate part which is much closer to the finished shape of the component prior to the start of machining. The high material and resource wastage factors are thus avoided.

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Traditionally, comparisons between manufacturing routes have been performed on an individual component basis. Whilst being totally specific to the component under scrutiny, it is difficult to apply this process in the generic case since definition of variables such as machine cost rates, raw material costs, labour costs, and material wastage factors are difficult to define in an absolute sense.

The aim of this work is to provide a generic overview of the relative economics of producing a near net shape by additive manufacturing processes compared with traditional machine from solid processes. In this way, ball-park, target specific costs required to achieve the economic use of additive manufacturing processes can be defined, thus enabling the general viability of possible applications for Additive Manufacture to be assessed for present and future scenarios.

1.2 Definition of Terms

1.2.1 Near Net Shape

This is defined as a part finished component which is ready for finish machining. In the machine from solid route this stage is reached following the roughing operation which removes the bulk of the material. In the additive manufacture route a slight ‘overbuild’ (equivalent to the allowance left for finish machining in the MFS route) over the finished component shape is usually provided to allow for removal of surface finish effects and to allow for slight thermal distortion effects on cooling.

1.2.2 Additive Manufacturing Process

The method of operation of the additive process is left open for the purposes of this comparison. Systems which could be considered are:

- Blown powder + Laser
- Powder bed + Laser
- Wire + Laser
- Wire + Electron Beam
- Wire + TIG

Each system has its own unique attributes in terms of process variables such as; deposition rate, heat input, processing atmosphere, precision of deposition, raw material usage efficiency, etc. which will determine the most favourable method for individual applications. The specific cost per unit weight of the deposited material is used as a basis for comparison. Factors such as raw material cost, deposition rate, machine capital cost, etc. are used to generate the specific cost of the deposited material.

1.2.3 Terms of the Comparison

The comparison looks at two ways of manufacturing the same near net shape. Firstly by traditional machine from solid using a forged billet as the starting point and secondly by an AM process. From this point on it is assumed that the rest of the manufacturing route to completion of the part (ie finish machining, cleaning, inspection etc.) is identical for both routes.

1.2.4 Machine from Solid Start and Finish Situations

The situation is shown diagrammatically on fig. 1 below for 2 typical machine from solid scenarios. The first from a ring rolled forging and the second from a parallel sided block.

The Volume of the original Billet = V
The Volume of the near net shape = v

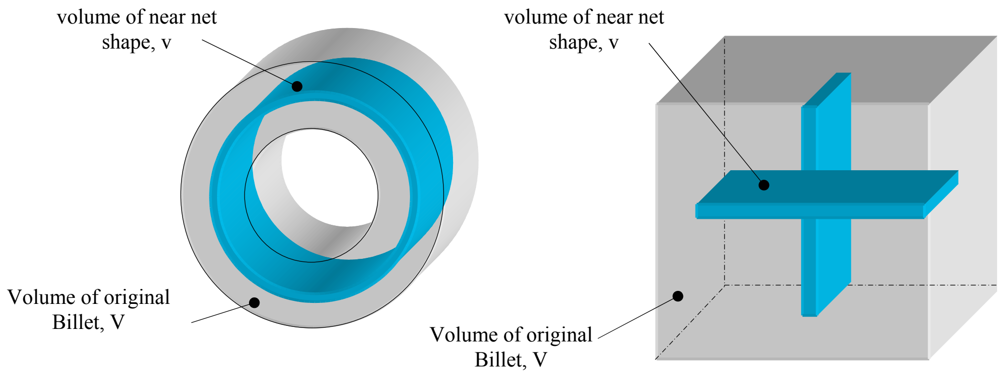


Fig.1: Diagram showing start and finish in the machine from solid route

The closeness of the shape of the raw material forging to that of the finished component is primarily a function of the precision to which the forging process can work in the particular material.

A variation of the forging process commonly used for aero engine components is The Seamless Rolled Ring Forging Process. A forged circular billet is first pierced to form a ring which is then is hot-rolled between vertical and horizontal rolls as shown in fig.2.

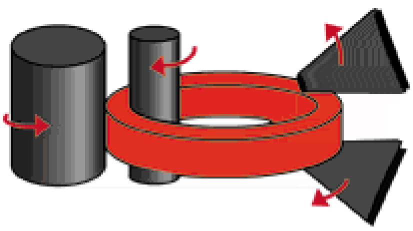


Fig.2. Diagram of the ring

In the case of Titanium, a minimum section thickness of about 25 - 30mm is imposed. The rate of heat loss from the billet during rolling is dictated by the section thickness. (ie; thin sections cool much quicker than thick ones). Below 30mm the billet does not stay hot enough for long enough to complete the rolling cycle. Breakage of the rolls will result since Titanium is a relatively strong and brittle material when below its forming temperature.

A machining allowance is also provided to allow surface effects such as skin stresses and oxidation caused by the forging process to be machined off. As a rule of thumb designers traditionally specify an overall envelope of about 5 - 10 mm around the finished component to ensure that the component contains no material with surface effects.

1.2.5 Buy:Fly Ratio

A term commonly used to compare the size of the original billet to that of the finished part is the Buy:Fly ratio. ie the simple ratio of the weight of the component as installed in the aircraft referred to the weight of the bought-in material prior to machining.

Buy:Fly Ratio = B = V/v

Table 1 lists the start weight, finish weight & corresponding Buy:Fly ratios for some typical titanium aero engine components:

Table 1: Billet weight, Component Weight and corresponding Buy: Fly ratios for some Aero engine components

Component	Billet weight (kg)	Component wt (kg)	Buy:Fly
Intercase	182	30	6.06:1
Simple Duct Flange 1	67	11.14	6.01:1
Simple Duct Flange 2	67	7.66	8.75:1
Complex Duct Flange 1	149	7.65	19.48:1
Complex Duct Flange 2	206.6	10.28	20.10:1
Large Blisk	810	97	8.35:1

1.2.6 Additive Manufacture Route Start and Finish Situations

The starting point for the AM route is taken to be the purchase of the raw material in either wire or powder form.

The Finish situation is the near net shape. At present, it is usual at present to provide an 'overbuild' of 1 - 2 mm on all near net surfaces. This is to allow surface finish effects such as surface roughness and imprecision due to cooling to be accommodated. It is analogous to the machining allowance left on the part finished machine from solid component after rough machining prior to finish machining.

1.2.7 Machine from Solid Costs

In simple terms, this is expressed as the cost of buying the original billet plus the cost of machining off the excess material. (For simplicity, tooling and set up costs have been ignored.)

The cost of buying the billet: $C_{mat} = V.\ \rho.\ C_f$

where: V = Volume of original Billet (m^3)

ρ = Density of Titanium = 4,460 kg/m^3

C_f = Specific cost of ring rolled forged material. (£/kg).

The cost of machining off the excess material: $C_{mcg} = (V\text{-}v).\ C_m$

where: $(V\text{-}v)$ = Volume of material to be removed (m^3)

C_m = Specific cost of machining off the material. (£/kg)

$C_s = (V.\ \rho.\ C_f) + (V\text{-}v).\ \rho.C_m.$

1.2.8 Additive Manufacture Costs

The additive manufacture route takes raw material in the form of powder or wire and builds up near net shape.

The cost of producing the near net shape is therefore simply:

$$C_a = v.\ \rho.C_d$$

where:

C_d = Specific cost of Deposited Titanium. (£/kg).

2.0 COMPARATIVE COSTS OF ADDITIVE MANUFACTURE V. MACHINE FROM SOLID

The cost estimates derived from relationships based on the specific costs of adding and removing material can be used to compare the costs of making a near net shape by the two routes under scrutiny.

From the approach taken above it was found that, to a first approximation, the cost of providing the near net shape by the Machine from Solid route,

$$C_s = (V.\ \rho.\ C_f) + (V-v).\ \rho.C_m.$$

Similarly, The cost of producing the near net shape is:

$$C_a = v.\ \rho.C_d$$

It can be seen that there is a trade off between buying and then machining off a relatively large volume of material at lower specific costs in the MFS case against depositing a lower volume of material at higher specific cost in the AM route.

To find the break even point of the comparison the costs of near net shape manufacture from the two routes are equated;

ie: $C_s = C_a$

It can be shown that:

$$B(C_f + C_m) - C_m = C_d$$

To get a feel for the situation needed to return a 30% cost caving by the use of AM we can set:

$$0.7C_s = C_a$$

in this case we find:

$$0.7[B(C_f + C_m) - C_m] = C_d$$

From this simple relationship it can be seen that additive manufacturing techniques will be attractive over conventional MFS techniques in the case of components which:

- have a high buy:fly ratio
- have a complex shape which involves a lot of machining
- have a high cost of raw material used for machining from solid
- have slow machining rates
- are difficult and expensive to machine

Equally, the lower the specific cost of the deposited material, the more attractive it is.

With the aim of producing a diagram which shows the general area in which Specific costs of the AM have to lie in order to compete with traditional MFS methods the following relationship was generated.

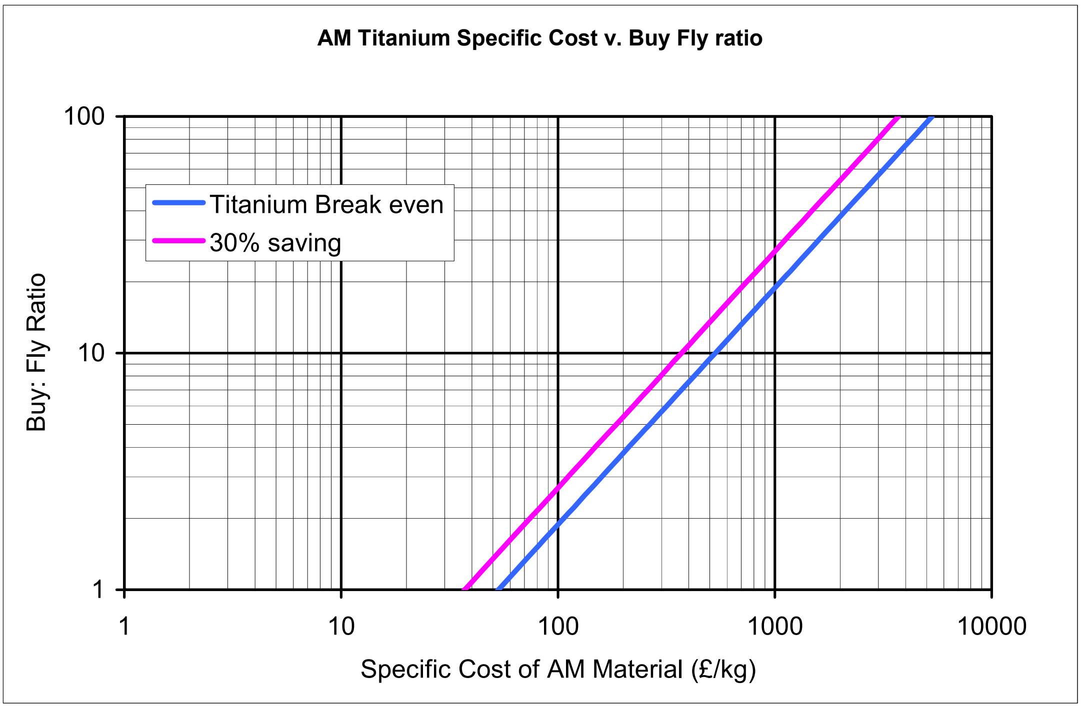


Fig.3: Specific Cost of Additive Manufacture Titanium required to compete with Machine from solid methods for a range of Buy:Fly ratios

From this diagram it can be seen that, to a first approximation, for the range of typical Buy:Fly ratios encountered on aero engine components of 6:1 to 25:1 the specific cost of the AM material has to lie in the range of £200 to £1000 per kilogramme.

The above estimate is for a scenario where a one off is to be made entirely by AM. In many ways this represents the worst case. Other Titanium scenarios which could be considered are:

- 'hybrid' manufacture, where AM is only one of a range of processes used to produce the component. An example would be the addition of bosses and 'features' to the carcase of an Intercase which has been made by conventional fabrication techniques.
- repair, where relatively low volumes of deposit are used to reclaim high value components
- comparison with fabrication. Titanium is not as straightforward to form and fabricate as, say, mild steel since special techniques such as hot creep forming have to be used to form the material and welding has to be carried out in inert conditions to avoid oxidation problems.

These scenarios would tolerate higher specific costs for AM material and still be economically beneficial.

3.0 SPECIFIC COSTS OF ADDITIVE MANUFACTURE MATERIAL

Having estimated the general range in which the specific cost of AM material has to lie in order to be economically competitive re: conventional MFS techniques, we will now consider the specific costs of deposited material to see if AM processes are capable of working advantageously. The variables considered are as follows:

- **Material Density:** Additive Manufacturing Processes tend to work in terms of volumetric deposition rate. To estimate gravimetric rates the material density is required. A figure of 4.46 g/cc is used for Ti 6-4.

- **Raw Material Cost:** The Cost of the as-bought raw material is used. The cost per kilogram is very dependent on the amount ordered, especially in the case of powder.
- **Material Usage Efficiency:** For wire raw material this is 100%. The figure for powder systems varies widely from 10% to 90% depending on the actual system. This inefficiency effectively puts an on-cost on to the raw material. eg if the material costs £50/kg to buy in and is used at 50% efficiency, then an effective cost of £100/kg is being paid. It may be possible to recycle the powder, in which case the on-cost is not incurred. For the purposes of this estimation it is assumed that recycling is not viable for aerospace components due to the risk of contamination during the reclamation of the waste material.
- **Process Labour Cost:** Most systems need constant attention of some sort or another from a process operator. If the system is fully automatic then a figure of zero is entered.
- **Capital Cost:** Total cost of the AM system and ancillaries as bought from the supplier.
- **Machine Utilisation:** This is the number of hours per year the machine will be used. A standard, single shift figure of 2000 h/yr (ie: 8 h/day, 5days/week, 50 weeks per year is used).
- **Power Cost:** This is the cost of the electrical power as bought from the national grid.
- **Power Conversion Efficiency (wall:delivery).** All welding power sources are not totally efficient at converting power drawn from the wall into heat energy used for the welding process. TIG sources are assumed to be 60% efficient. Laser efficiencies are typically low viz: Nd:YAG is 3%. CO_2 is 7% and Diode is 25%.
- **Power delivered:** This is the power setting used as one of the 3 main deposition parameters and is the power delivered from the heat source to the job.
- **Build Rate:** This is the build rate given by the parameter set in operation at the time of deposition expressed in the conventional units of cm^3/h.
- **Consumables:** An estimate of the consumables used hourly by the particular system is entered here. For arc based systems these variables include; tungsten electrodes, wire feed guide tips, gas lenses, torch gas, process gas etc. For laser based systems these variables include; lamps, coolant, lenses, process gas etc.

Fig.4 shows the variation in the cost per kilogram of deposited material v. the rate at which it is deposited.

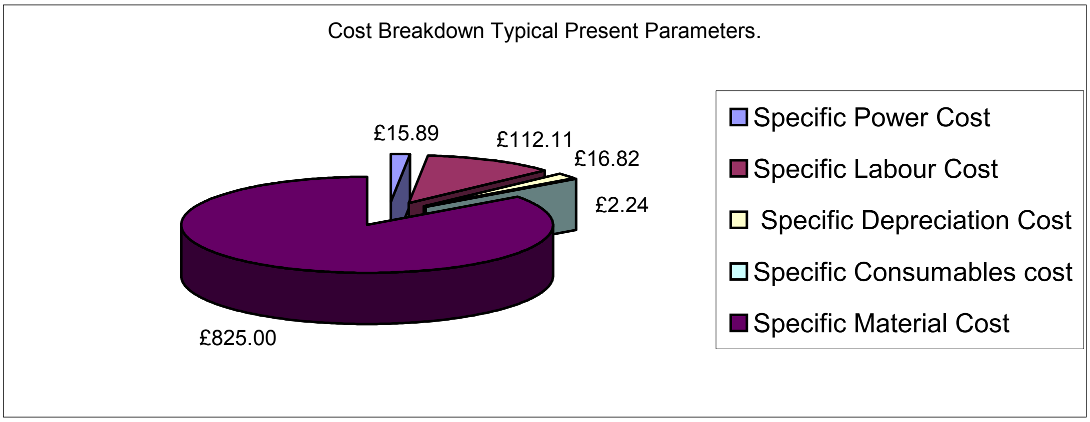


Fig.4: Breakdown of costs of producing a kilogram of Ti 6-4 using typical present parameters

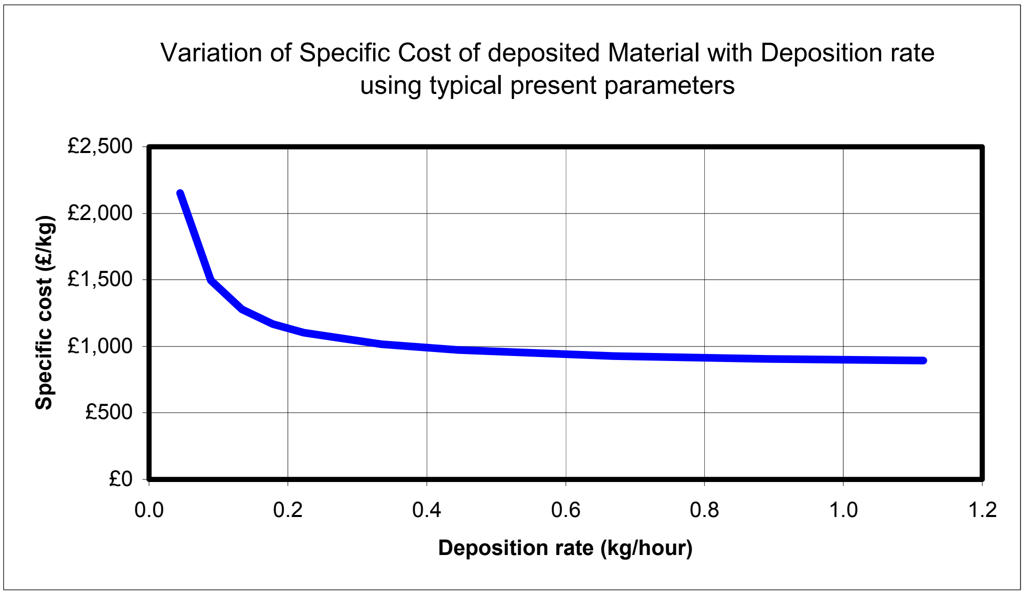
It can be seen that the specific cost falls rapidly from the £2153/kg deposited at 50g/h as the deposition rate rises. For example, at 300g/h the specific cost has halved. Above about 400g/h the specific cost asymptotically approaches the powder cost.

A total cost of £972/kg of deposited material is now shown by the cost model which is just inside our target window of £200 - £1000/kg. The pie chart shows that 85% of the total stems from material The areas to aim at to further reduce costs are therefore; on the machine design side to increase material deposition efficiencies and on the raw material side to reduce powder purchase costs.

3.1 Specific Costs of Future Deposition Systems:

Looking into the future, the following changes are likely which are expected to further reduce the specific cost of deposited material:

- **Powder costs:** New methods of manufacturing Titanium Powder are under development at present which claim to have the capability of producing titanium at 10 - 20 % of the cost of current routes.
- **Labour Costs:** Fully automatic operation of the machine is being actively pursued by system builders. Future systems will accept 3D CAD files in electronic format and convert the electronic model into metal without guidance from the operator.
- **Powder Usage Efficiency:** At present powder usage inefficiencies stem mainly from the inability to focus all of the powder stream into the small spot sizes (c.1mm dia.) used. As deposition rates increase then a move to larger spot sizes will probably be involved. A figure of 80% is seen to be achievable.



- **Laser Power Conversion Efficiency:** The Nd:YAG lasers used at present convert only about 2 - 3% of the power drawn from the wall into power delivered to the job. The rest is lost as low grade heat. The best type of power source for future applications is seen as the diode laser which has a conversion efficiency of c.30% or fibre laser which has theoretical efficiencies of up to 80%.
- **Deposition Rate:** A deposition rate of 2kg/h is used here as a reasonable figure to be attained by future systems.

The cost breakdown for Titanium produced at a rate of 2kg/h is shown in fig.5 below:

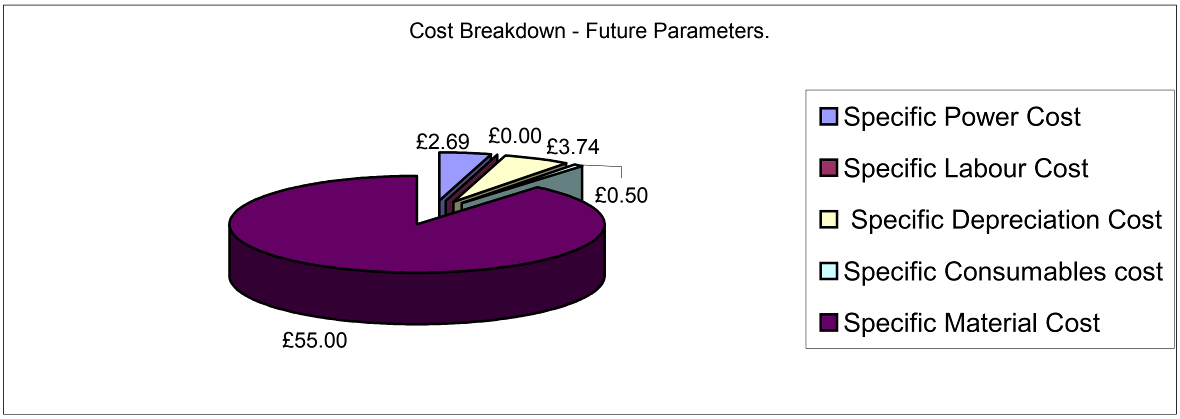


Fig.5: Breakdown of costs of producing a kilogram of Ti 6-4 using future parameters

A specific cost of about £62/kg is therefore estimated for material deposited at about 2kg/h by future systems.

4.0 CONCLUSION

From the analysis detailed above, from a specific cost of material deposition point of view there is much scope to reduce the figure from the c.£2000/kg deposited by the first generation of commercial machines to less than £100kg for future generations. This will enable components with conventional buy:fly ratios in the 2 - 3: range to be competitively manufactured as OEM by AM techniques.

MEETING DISCUSSION – PAPER NO: 17

Author: J. Allen

Discusser: D. Dicus

Question: How did you derive the specific cost (£825/Kg) that you showed as your first example?

Response: Put together a spreadsheet containing the variables stated. Reduced everything to cost/unit time. Referred this to the deposition rate, found the data shown.

Discusser: P. Kobryn

Question: Have you considered the comparative costs of ancillary operations such as intermediate stress relief, heat treatment, and special NDI in your cost analysis?

Response: The analysis was very much a first look at the economic viability of additive manufacture, and issues mentioned above were not included. It is hoped to develop the work in the future to include these variables. We understand NDI of complex structures is an issue. Our approach is to say that future systems will be self checking for material structure and inclusions in an on-line situation. We also realize that these sensors are not fully available today. One of our development areas is to encourage the realization of such systems. The analysis also assumes that intermediate stress relief will not be required by this AM process used in the future.

Discusser: V. Samarov

Question: The more complex is the shape, the more will be expenses for is NDI (compared to relatively cheap ultrasonic inspection of primitive blanks). What will be the added cost?

Response: Please see immediately preceding question for technical requirements. The additional cost will be seen in the capital cost of the machine. This will be seen in the capital write off section of the specific cost/kg pie chart.