Manufacturing impact assessment for remanufacture of a forging die

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Abstract

Methods to reduce energy use and carbon emissions are of increasing interest and importance to manufacturers. Carbon pricing and environmental legislation is likely to make them even more so in the future.

Remanufacturing (reman) has significant potential to reduce embodied energy and carbon emissions. To fully understand this impact, the savings must be measured. In addition, to make these values meaningful, they must be compared to a baseline (e.g., conventional manufacture (CM)).

This paper presents a framework for manufacturing impact assessment, suitable for use in the manufacturing sector. The method is used in a case study of remanufacture of a forging die. The die was originally machined from H13 (a hot working tool steel) and reached end of life after 1300 cycles. During reman, the wear areas were rebuilt using laser metal deposition of Stellite 21 and, after machining, the die went on to operate for another 1400 cycles.

A cradle-to-gate life cycle analysis (LCA) was carried out to compare the two methods. The model was challenging to develop because of the sparsity of available data available on additive and powder manufacturing processes. Despite this, the analysis considers the impact of the materials and processes used in both reman and CM routes, to give a robust comparison.

The results show that the energy and CO_2 eq. used in reman is a reduction of over 99% compared to the CM. It is reasonable to claim that, for other CM/reman cases of this type, results should be similar because the largest impact was the reduction in the quantity of material used.

Background

Life cycle analysis

The life cycle analysis (LCA) process is a conceptual framework for assessing the environmental impacts of a product. This process looks at the constituent or contributing elements (inputs) of the product and attempts to measure the external impacts (outputs). A full LCA contains the five inputs: resource extraction; manufacture; distribution/logistics; use; and disposal. Many outputs are possible, but they typically fall in the areas of environmental, social, and economic impacts.

Many forms of LCA are possible, including a selection of these inputs and outputs in greater or lesser detail. In this paper, the scope includes the outputs of embodied energy and carbon dioxide equivalent (CO2eq) emissions. It has been shown that even simplified calculations of embodied energy can give a reliable final estimate [1].

Remanufacturing

Governments across Europe and (EU) policymakers have set net zero CO_2eq emission targets for 2050. Meeting these targets will impose significant challenges on the manufacturing sector. Studies have shown that 45% of the emissions are produced in manufacturing [2]. Remake, which includes remanufacturing, repair, reuse and repurpose, will be a significant contributor to achieving net-zero. Remanufacturing (reman) is the process of bringing used products to a "like-new" functional state by rebuilding and replacing their components [3]. It has the capability to reduce CO_2eq emissions, energy consumption, raw material use, and the release of toxic chemicals to the environment [4]. Reman will therefore be a significant contributor to national net zero targets.

An accurate calculation of the carbon emission savings is required to justify the use of reman on environmental grounds. Reman can reduce energy and material use, however this is not always the case as Gutowski et. al. show [5], therefore a calculation of emissions is needed for each case.

The National Manufacturing Institute Scotland (NMIS) has a broad range of remake development activities, utilising technologies such as additive manufacturing (AM), NDT and AI to optimise remake processes. Work at NMIS aims to validate the promise of carbon emission savings using AM technologies for remake in comparison with virgin manufacturing.

Carbon accounting and Remanufacture

It is sometimes taken as a baseline assumption that remanufacturing is certain to provide energy savings and environmental benefits over conventional manufacturing. And in some cases, energy and material use can be reduced significantly [6]. But in fact, the benefits are contingent on the details of the case [7]. Results which that apply to relatively complex, multi-material, low- or medium-value products (consumer goods, electronics, automotive) may not apply to reman of heavy industry components (forging dies, presses).

Indeed, there is evidence that remanufacturing of some products is worse for the environment [5]. This means that, when making claims for the environmental value of a reman process, it is not sufficient to rely on implicit assumptions about environmental benefit. Claims of environmental (or other) benefit need to be made clear and explicit, and justified with evidence. Only then can they be used to justify the pursuit of reman for a specific product or component.

Method

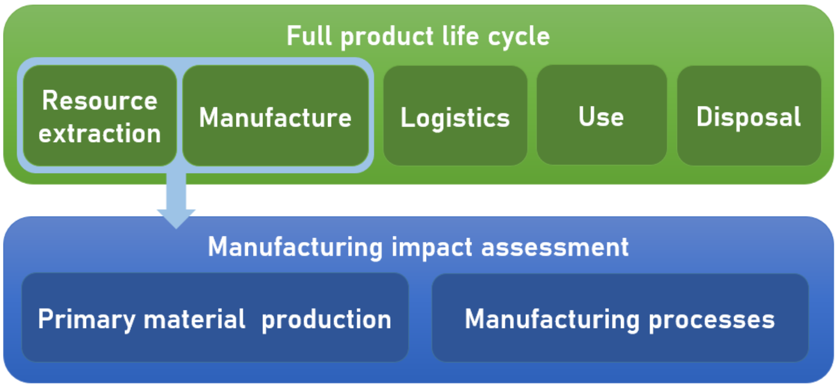
This work was carried out as part of a project at NMIS, developing a framework which can be used to assess the environmental impact of different manufacturing process. This framework can be used to compare alternative manufacturing routes (as in the case study here) or to assign a value to the energy-intensiveness of a current or prospective manufacturing process.

The approach is called manufacturing impact assessment and is intended to be useful for manufacturers and those in the manufacturing supply chain. It is not intended to be fully comprehensive, or to calculate all outputs with pinpoint precision. Instead, it aims to produce useable approximate figures, and to collect data sources. These will allow future work to expand the scope covered and improve the precision.

Scope for calculations

As with any model, an LCA uses a subset of all possible inputs and outputs and relies on simplifications. A complete LCA would be an analysis of the product's entire life cycle (cradle-to-grave). This can be broken down into five categories: resource extraction, manufacture, logistics (including reverse logistics for reman), use and disposal. It includes many impacts which are far outside the control of the manufacturer.

Figure 1: Full LCA and Manufacturing impact assessment



Assessing these elements of the LCA is challenging without the engagement of industrial partners through the entire logistics, use and disposal supply chains. Many companies do not measure or assess environmental impact or are unwilling to share it for reasons of commercial sensitivity. In addition, decisions about logistics (e.g., air vs rail distribution of products), use (e.g., maintenance for in-service life extension), disposal and reverse logistics can have huge impacts on the total lifetime emissions associated with a product. Manufacturers have little capacity to influence these later product life stages.

When considering the environmental impact of the manufacturing supply chain itself, it is logical to focus on the impacts which are within the control of the manufacturer. This approach is termed cradle-to-gate (CTG), referring to the inputs and processes before the product leaves the factory gates. This approach focuses on the impacts that a manufacturer can readily measure and alter. To capture these impacts under manufacturer control, CTG is the approach that represents the best combination of detail and usability for the manufacturing supply chain.

The scope here will be limited to embodied energy and CO_2eq as these are the key impacts and most readily measured. Other emissions to soil and water, or further environmental and non-environmental impacts will not be considered. The CO_2eq will be derived from the total embodied energy of manufacturing - this measure is less subject to variation (for example being independent of variations in the CO_2eq emitted per unit of grid electricity).

Data sources and estimating methods

Data is key to the LCA process. The basic facts about the materials and processes must be recorded in sufficient detail to allow the construction of a rigorous LCA. Wherever possible, these values (quantities of material input and wastage, time durations of processes) should be recorded directly. Where this is impossible, information should be obtained indirectly from suppliers. The main sources of data required concern materials, processes and other consumables or contributors. If this information is not available, the inputs must be estimated.

The impact of primary material production on the total energy use in manufacturing is significant. Combined figures for the energy and emissions associated with primary material production are sometimes available. These encompass all component processes in material extraction, purification, and transport before the material purchase for manufacture. In general, conducting a detailed analysis of the emissions involved in these areas would be an inefficient use of resources for manufacturers, since there is little scope to alter these values. A combined value represents a useful simplification when it can be obtained. Generic values for many materials are available, from a variety of materials and LCA databases. Suppliers may also be able to provide this data.

Processes carried out by the manufacturer or remanufacturer can be well documented and therefore have good data which can be used to calculate the impact. In many cases, though, there is no data, and values must be estimated.

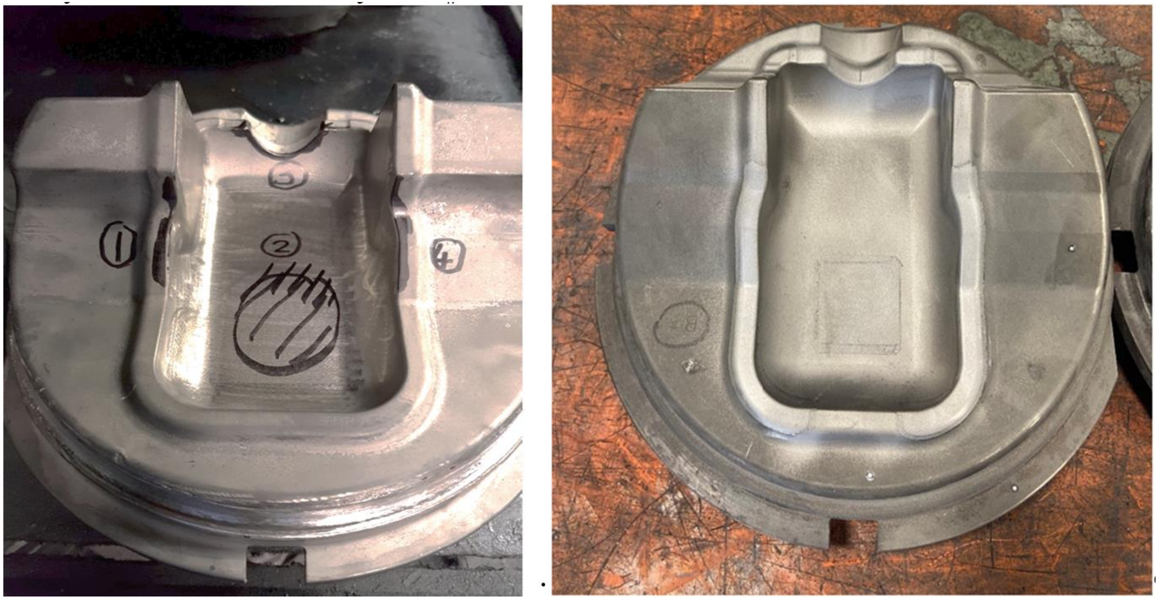
There are numerous other possible impacts. These include treatments, lubricants, coolants, chemicals, coatings, the impact of tool manufacture, and other energy costs. Data for these is often limited or non-existent. It is good practise to name any other contributing factors even if they cannot be evaluated quantitatively.

Where direct or indirect data is not available estimates must be used. Working off data from similar or analogous materials and processes can give plausible values. These estimates should be made conservatively, i.e., tending towards worst-case scenarios.

Case study: DigiTool project

DigiTool was an Innovate UK funded project, carried out by a consortium of the NMIS and 5 industrial partners which developed a remanufacturing process for a closed die forging tool. The die, made of nitrided H13 (a chromium die steel used for hot forging applications), was used for forging forestry vehicle components from a boron-steel alloy. These dies typically reached end-of-life (EOL) after 1300 forging cycles due to wear in several key areas. The remanufacturing process consisted of preparatory machining of worn areas, deposition of Stellite 21 and finish machining, and aimed to produce a tool capable of at least another 1300 cycles. The remanufactured die met all dimensional criteria and went back into service. It operated successfully for another 1400 forging cycles, with the repaired areas showing less wear than the base die material.

Figure 2: Die at EOL with areas of wear marked (left) and after remanufacturing (right)



Information about the manufacture and remanufacture was assembled, alongside estimated data where the underlying data was unavailable, to make a comparison of the two processes in terms of their energy and CO_2eq. emissions.

Conventional Manufacture

The existing route to manufacture is machining from a solid block. Use of detailed information about the manufacture is limited by commercial constraints. Therefore, secondary data is used to characterise the process.

Material production

The die is made of H13 tool steel. Energy and CO_2eq values for the primary material was obtained from *ANSYS GRANTA Edupack* [8]. The nominal starting billet was calculated as being the minimal cuboidal billet which would fit the die (228x255x129 mm). It was assumed that no material was wasted cutting the billets to size. It was assumed that energy recovery from swarf recycling was negligible.

Manufacturing processes

It was assumed that the part was machined from the solid block (i.e., not cutting or sawing to size). The mass of material removed was calculated using the volume of the solid model (2904 cc). The breakdown of the machining was estimated as 95% coarse machining, 4% fine machining, and 1% grinding, with values from [8]. It was assumed that no heat treatments or coatings were used in the manufacture. It was assumed that no energy was recovered from wasted materials. Table 1 shows the values for conventional manufacture.

Table 1: Results for conventional manufacturing route

Contributor	Amount (kg)	Energy (MJ)	CO_2eq (kg)	Source
Production of H13	58.500	3793.8	278.75	[8]
Machining	35.850	132.2	9.92	[8]
Total (rounded)	-	3925.9	288.67	

Remanufacture

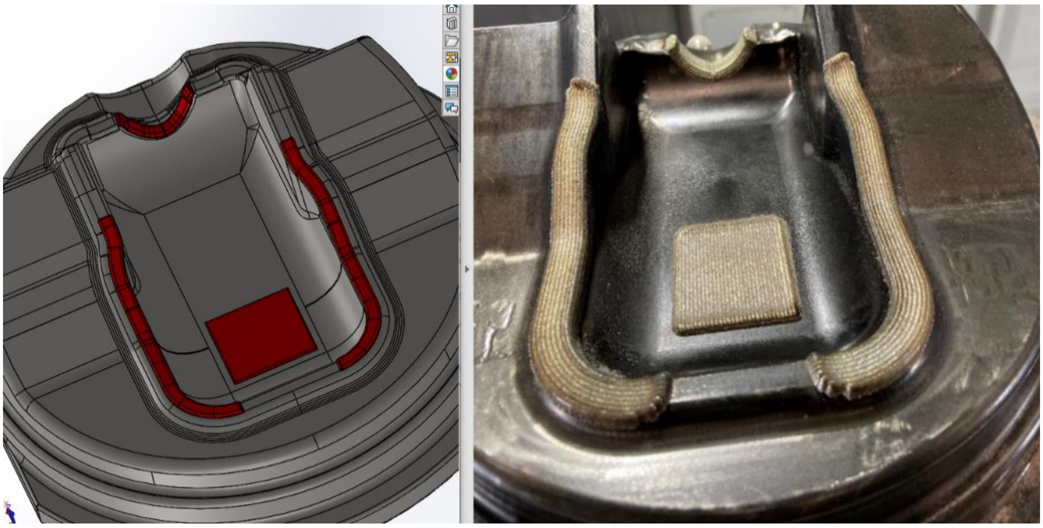
The remanufacturing process consisted of machining back the worn die areas, depositing Stellite 21 with a powder additive process called liquid metal deposition (LMD), and then finishing machining the die.

Material production

The material used for the additive manufacture was Stellite 21. It was not possible to obtain values for primary material energy and CO_2eq, so values for the similar alloy Stellite 6K were used instead [8]. The atomisation energy to turn the material into powder is not readily available for less common alloys. The atomisation value was used for Inconel 625, a nickel-chromium-molybdenum alloy [9].

The amounts of material removed and deposited were estimated by creating a 3D model of the process based on the published information about the project [10,11].

Figure 3: CAD model and photograph of die after stellite deposition



Manufacturing processes

The volumes for the preparatory machining and finish machining were obtained from 3D modelling based on the description from Devine et. al. (2021) [11]. It was assumed that the finish machining was 90% fine machining and 10% grinding, with values from [8]. Note that the energy attributed to machining is related to the material and differs for H13 and Stellite 21 (where the Stellite 6K approximation was used as above).

The duration of the LMD process was calculated as 759 seconds based on the amount of material deposited (assuming a 50% material wastage rate) and the powder flow rate (7g/min). The energy required for the LMD process was estimated from the length of the procedure and the wattage of the deposit head (1200 W); it was assumed that the machine operated at an efficiency of 10% to account for losses in generating the laser beam.

Argon was used at a rate of 5 l/min for nozzle gas, 9 l/min shield gas, and 5 l/min carrier gas. This is used with the estimated cycle time to calculate the volume of gas used. The density of Argon [8] was used with the embodied energy and CO_2eq from Wilson et. al. [13] to estimate the total energy. No estimates were made for cleaning of the die prior to remanufacturing. It was assumed that no energy was recovered from wasted materials. Table 2 shows the values for remanufacturing the case study dies.

Table 2: Results for remanufacturing route

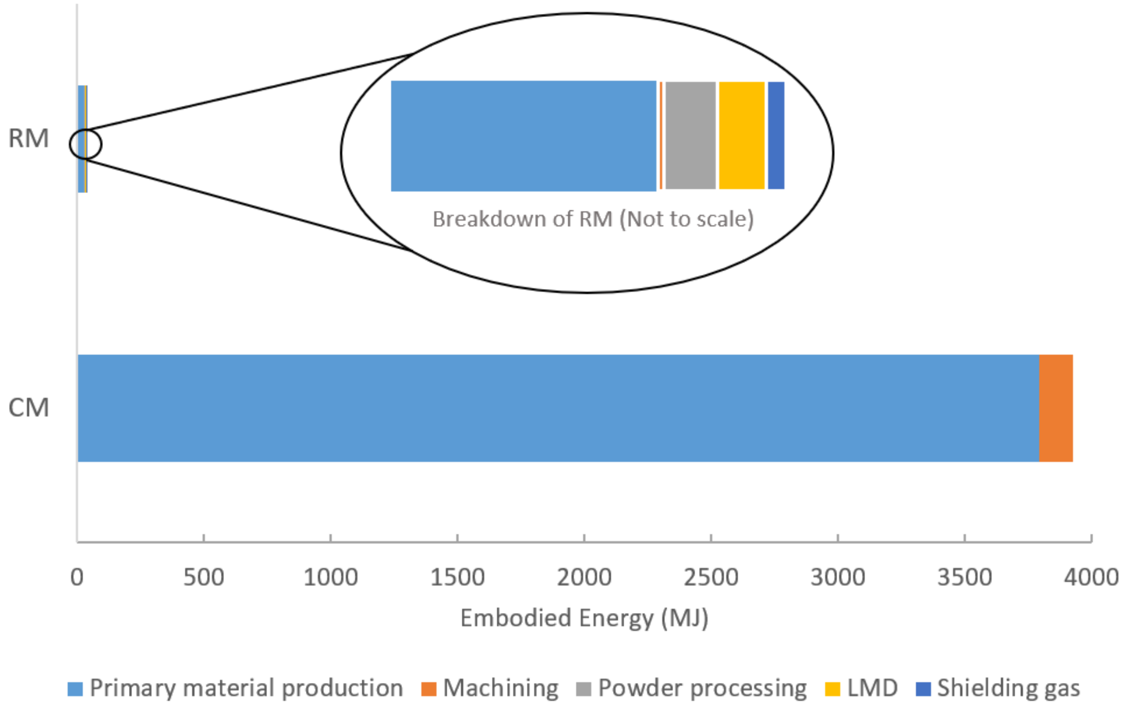
Contributor	Amount (kg)	Energy (MJ)	CO_2eq (kg)	Source
Production of Stellite 21	0.089	24.7	1.17	[8]
Powder manufacture	0.089	4.9	0.38	[9].
LMD	0.044	4.6	0.35	[10,11]
Shielding gas (argon)	0.425	1.9	0.08	[8, 12]
Machining	0.044	0.5	0.04	[8]
Total (rounded)	**-**	**36.6**	**2.02**	

Results

The results combine the values found by modelling, research, and estimation. Figure 4 shows the values for CM and reman respectively.

There are two major features of these results: firstly, that the remanufactured case uses barely 1% of the energy, and secondly that or both routes, primary production of material dominates the impact. Even significant changes in the assumptions would not bring the results close together, which suggests that it is reasonable to place some weight on the outcome. That is, it is safe to say that the remanufacturing process has a much smaller energy impact and CO_2eq emissions. In addition, the results show that embodied energy and CO_2eq are proportional. This is a result of the assumptions made in this case and may not be true for all manufacturing processes.

Figure 1: Embodied energy in the two production routes



Discussion

Limitations

The assumptions and simplifications presented above mean that there is some uncertainty about the accuracy of the results. Notable limitations are the absence of information about energy recovered from machining waste and the impact of any coatings or heat treatments. This is particularly important for conventional manufacturing. The parameters relating to the powder manufacture and LMD process are more uncertain than those relating to primary material production and machining. In general, conservative assumptions have been made where information is limited, so that the results for both routes are likely to be closer to a worst-case scenario than the true value.

Future work

The manufacturing impact assessment would benefit from an expanded scope and greater precision. If the scope included forward and reverse logistics, cleaning, and material disposal, better comparisons would be possible against other manufacturing processes. Greater precision would be best achieved by gaining more accurate and relevant data as a basis for calculations.

This work has shown that little data is available around the powder production processes. As powder-additive technology can form a substantial part of remanufacturing, especially in high-value components and assemblies, more and better data collection would be beneficial. Machines will require further data collection points, to determine the exact usage of various inputs, such as gas, air, water, power etc.

Those data could build a database to be able to calculate more accurately a broader range of remanufacturing processes and components. More research must be conducted, to understand the impact of various remanufacturing processes. This will support decision-making around the value retention process. FEA simulations could be developed to understand the additional material and process usage required.

Conclusions

The analysis presented here suggests that the energy and CO_2eq in the remanufacturing process is a reduction of over 99% compared to the conventional process. Accounting for the number of cycles in use, if every die were remanufactured just once before EOL, the total energy used in die manufacture would be reduced by 51%.

It is reasonable to claim that, for manufacturing of this type, results should be similar. The key feature of this case is the difference in material used. By extension, other remanufacturing processes that reduce material consumption will tend to reduce emissions. For future case studies, the use of material should be considered of prime importance.

Authors' contribution

A.R. was the project sponsor. A.A. conceived the method and carried out the estimations and calculations for the case study. A.A. and A.R. collaborated on the manuscript.

Acknowledgements

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