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(Research Article)

Revolutionizing Efficiency: A Strategic Redesign of VMC Machine Base Casting for Enhanced Productivity and Cost Optimization

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Abstract

Redesigning and developing the base structure of a Vertical Machining Centre (VMC) represents a significant endeavor in the realm of manufacturing and machining technologies. Nowadays VMC has a conventional structure design having too many ribs and cores. That conventional method of structure design involves an orthodox mindset related to ribbed structure design in addition to the conventional method of pattern making and casting methodology. Industries need to advance VMC machines productively and cost-effectively for mass production. The present work is done for the redesign of the VMC machine base with the use of Finite element analysis software along with a detailed study of foundry practices to eliminate certain issues like multiple core design, core setting method and time, draft angle consideration, limitation of rib thickness, etc. In essence, the primary objective of this research is to create the best possible design of the base structure of the VMC machine such that increased productivity and cost-effectiveness with higher stiffness as compared to the conventional design of the base. In summary, the research involves a holistic approach to redesigning the VMC base structure by leveraging structural analysis and applying advanced optimization techniques such as shape, size, and mass optimization. By systematically evaluating, refining, and validating the design through analytical and experimental methods, the objective is to develop a more efficient, reliable, and cost-effective base structure for Vertical Machining Centers in modern manufacturing applications.

Keywords: Base structure of VMC, Stiffness, Finite element analysis, Shape optimization, Mass optimization

1. Introduction

Vertical Machining Center (VMC) is a machining center in which the spindle axis and the rectangular worktable are set vertically, which is suitable for processing Highly accurate and precise components, even with multiple procedures and complex shapes. The spindle cartridge is mounted in a housing that moves vertically which is known as the z-axis and the component is usually mounted on top of its table and performs standard 2.5 or 3-axis machining operations, using a 3D Cartesian coordinate system for its motion. It is utilized primarily as a metal cutting machine that is useful in cutting or shaping steel, aluminum, and other hard materials in a precision-formed or machined surface.

Aside from these, it can also be utilized for milling, boring, drilling, carving, engraving, tapping, thread cutting, and more operations. It is widely accepted in various end-user industries such as aerospace, automobile, defense, electronics, etc.

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The CNC vertical machining centers market is rising drastically due to growth in various sectors. In addition, the growing focus on additive manufacturing is also responsible for enhancing the growth of the vertical machining centers market in the coming years. During the past 10 years, there has been substantial growth in the demand for buildings, cars, and heavy machinery across the world. This increased the demand for fabricated products such as stamped metal parts, building products, fasteners, and heavy equipment. To meet the growing demand for fabricated products from end-users, fabricated product manufacturers are integrating CNC vertical machining centers as they facilitate easy tool changing and produce superior quality products. Therefore, the rising demand for fabricated products is expected to fuel the growth of the global CNC vertical machining centers market during the forecast period.

Jyoti CNC's extensive product portfolio, spanning from basic to advanced CNC machines, positions it as a key player in the Indian CNC machine market. Their ability to offer a wide array of options makes them convenient for businesses looking for metal-cutting solutions, further solidifying their presence and reputation in the industry.

Concerning Frost and Sullivan's analysis for FY2022 Jyoti CNC holds 8% of the total Indian market share regarding CNC machine tool consumption data [12].

To increase the market share Jyoti CNC is undertaking various productivity improvement projects to match with market demand in a competitive environment.

The base structure is the core component of CNC vertical machine tools, and its specific stiffness has an important impact on the dynamic and static performance of machine tools with a productive and cost-effective manufacturing process. To improve the base productivity and cost-effective manufacturing process considering the specific stiffness and natural frequency of a machine tool base, the original model was redesigned.

Firstly, an optimization design was carried out for the base to obtain the optimal material distribution under the working load. Then, inner ribs distribution as well as wall and rib thickness redesigned with the help of FEA structural analysis. Finally, the optimal wall thickness and rib design are found. The optimization results show that the quality and maximum deflection of the base is reduced, the natural frequency is improved, and the comprehensive performance of the base is greatly improved.

2. Preface

The following table summarizes the main parameters of the project machine, which are essential for the design process. The machine data is supplied by Jyoti CNC Automation, Ltd., Rajkot.

- C frame type vertical machining center with automated tool changer
- Travel in X, Y, and Z direction 800 mm x 500 mm x 500 mm.
- Size of the base structure L x W x H: 1650 mm x 1140 mm x 480 mm.

The material we selected for the structural elements of machine tools is Gary cast iron, grade-25 (GC-25). This material has excellent casting characteristics and superior properties that suit our design requirements.

The base is made with the Sand-casting method. Here a detailed study of each process is done to optimize productivity. Sand casting basic steps are shown below [5] [9]

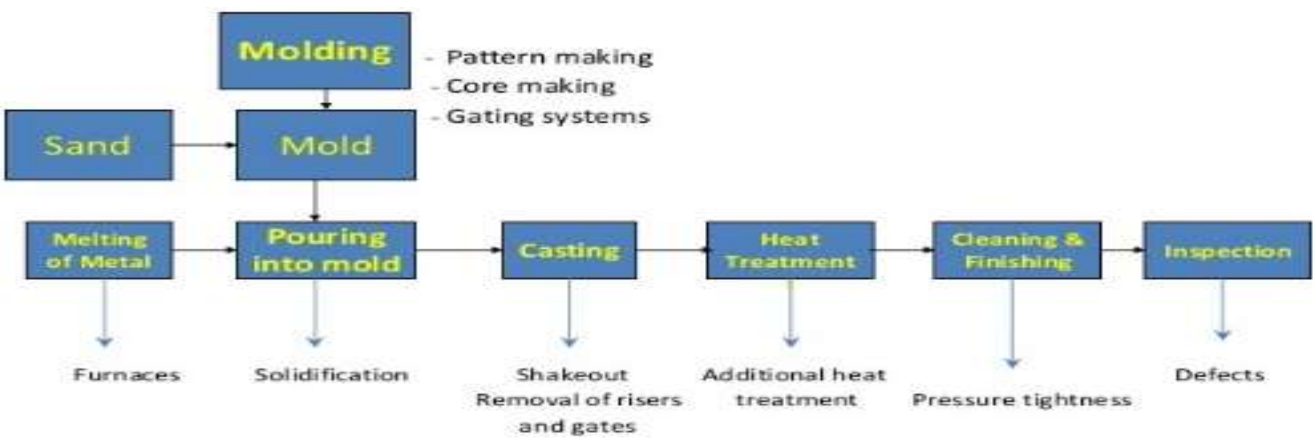

Figure 1. Steps in sand casting

2.1 Designing guidelines: While designing the critical cast iron components various design rules need to be considered for better casting part output and optimized process [1][5].

2.1.1 Draft angle: Draft angle is the angle applied or allowed on all vertical faces of a pattern to aid easy removal from the sand mold without damaging its walls. The angle required depends on the molding process, cast design, and pattern depth inside the mold. Design engineers often overlook this aspect of sand cast design even though it is critical for a successful cast. Allowing suitable draft angles and utilizing the tapered surfaces in the design will increase cast ability and reduce tooling costs due to increased metal flow and ease of tooling.

If it does not critically affect the functionality of the design, a draft angle as per ISO standards will help produce cheaper and more consistent sand molds. Generally, foundries as a rule of thumb use 1-1.5° of draft angle under normal conditions.

2.1.2 Parting line: A parting line in sand casting is the borderline in which draft angles change direction. Although the foundry will have the knowledge and experience of placing the parting line, engineering product designers should be aware of parting line placement as it dictates the quality and the cost of the cast. The parting line should be wide, short, horizontally flat, and placed as low as possible. Changes in parting line placement will affect core usage, gating placement, the weight of the cast, and dimensional accuracy.

2.1.3 Undercuts & cores: Undercuts in sand casts are features that prevent and stop the pattern from being removed during the mold-making stage. The usage of core sand loose pieces increases production time and cost. Parts should be designed in a way that reduces or eliminates core usage. Early parting line definition helps to understand the features to avoid undercuts.

2.1.4 Cross-sections: Uniform cross-sections, also referred to as uniform wall thickness are generally preferred but they are unfeasible in many engineering product designs. The principal requirement is not to leave thicker sections of the casting isolated when cooling. The thicker section takes longer to cool while all the metal around it has already solidified. As the thicker section continues to solidify it cannot "feed" from the sections around it leading to defects such as porosity or tearing. It is worth discussing with the foundry about the thickness limitation of your material before deciding [6].

2.1.5 Wall thickness: In sand casting, the volume-to-surface area ratio is critical in getting even solidification and avoiding the formation of cavities. Solidification is directly proportional to the square of volume/surface area ratio. Sections in the casting with low volume to surface area will solidify faster than sections with higher volume to the surface area.
It is good/ recommended practice to use ribs and gussets rather than increasing the overall thickness or adding thicker sections in load-bearing places. These not only add strength but also reduce localized thick walls and aid molten material flow.

2.1.6 Corners & angles: Cooling characteristics of the cast and mold material have a major influence on the quality of sand castings. Sharp angles at intersections and corners produce local hot spots and provide sources of stress concentration. This causes the cast to distort, shrink, and tear during and after the production process, hence should be eliminated by fillet radii.

2.1.7 Junction design: Since sand casting is a near-net shape manufacturing technique, the parts can often be very complex in shape and contain lots of junctions. These junctions are generally grouped under five types viz., L, X, V, Y, and X-T junctions.

They create localized mass concentrations, and these can create defects such as shrinkage, tears, and cracks. Ideally, these junctions should be designed in a way to reduce or eliminate localized mass concentrations.

2.1.8 Casting allowances: Most metals such as steel, aluminum, magnesium, zinc, and copper shrink when they solidify and need to be considered and managed carefully. The amount of shrinkage depends on the freezing point of the material and the volume-to-surface ratio of the product.

2.1.9 Machining allowance: Machining allowance should be added for mating interfaces of two sand cast parts and curved edges should be avoided at the interface. Recommendations for the machining allowances are included in the published standard ISO 8062.

2.1.10 Maximum portion should be in drag: For split patterns, the parting surface should be such that the maximum portion of the pattern remains in the drag.

3. Review of Existing Design and Optimization Scope

By reviewing existing parts with various designs on top of various manufacturing process aspects a checklist is prepared to support the redesign of the base.

Table 1. Exiting design parameters checklist

Sr. no.	Casting design rules and complete process parameters	Observation in existing design	Need to consider for new design
1	Draft angles	No draft angle was considered in part design	Need to consider
2	Parting lines	Ok	Ok
3	Number of cores and size	Too many cores of small size	Need to consider
4	Undercuts	Yes	Need to consider
5	Cross sections	Thicker sections in some area	Need to consider
6	Wall thickness	OK- can be optimized by FEA to reduce weight	Need to consider
7	Corners and angles	Some improperly designed corners are there	Need to consider
8	Junctions design	Many X, Y, and T junctions- need to be avoided or reduced	Need to consider
9	Casting/shrinkage allowance	Ok	Ok
10	Machining allowance	More @ 7mm per face	Need to consider
11	Maximum portion in drag?	No	Need to consider
12	Core handling and setting time	Too many small cores so handling and setting time are more	Need to consider
13	Fettling time	Too many cores – so more fettling time	Need to consider
14	Sand core coating – coat quantity and time	Cost quantity and time are more due to many small cores having more surface area	Need to consider
15	Accuracy of final cast part	Part-to-part variation	Need to consider

16	Ease of part handling arrangement	Ok	Ok
17	Overall throughput time	Throughput time, it affects the productivity of part	Need to consider
18	Raw material quantity	High	Need to consider
19	Machining time	High as more material allowance	Need to consider
20	Position and stiffness of level pads	Need to verify by FEA	Need to consider
21	Total cost	High	Need to consider

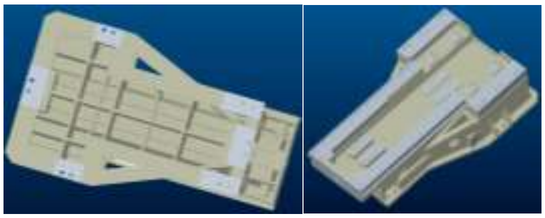

Figure 2. Existing base design bottom and top view

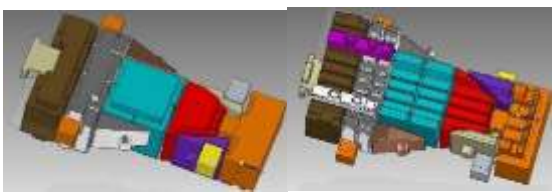

Figure 3. Existing base pattern design bottom and top view (Different colors show different cores)

4. Redesigning of Base Structure

The existing machine base dimensions were used for the primary design and structural analysis. The interfacing assemblies and the driving elements such as Ball screw assembly, guideways, machine leveling pads, etc. were kept the same as the existing design. Then, different design options were created based on various design and manufacturing method aspects, which were documented for reference. Next, the component behavior under different loading conditions was studied by performing various iterations on the dimensions and the rib structure. Cero software was used to design the Base structure.

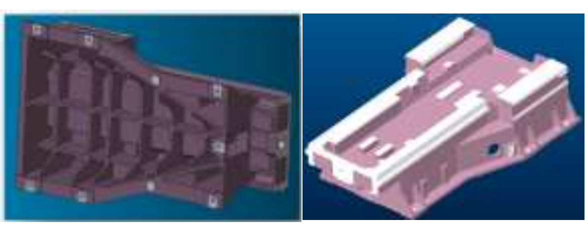

Figure 4. New base design bottom and top view

The design of the ribbing structure is crucial for the stability and performance of any structure. The ribs provide support and resistance to various types of failures and enhance the stiffness of the structure. To design ribbing structure, we have taken reference from N. K. Mehta and some other machine tool structure related books. [3][8] [10]. After completing the overall part design, the next step is to design the ribs appropriately. The effect of the stiffener arrangement on the base structure and its stiffness was also evaluated and compared with the existing base structure. The rib structure was optimized and then analyzed with the same loading and boundary conditions to compare the results.

5. Analysis of the Existing Model and Redesigned Model

The base is the key component of the machine tool, which is connected to the column and axis slides. Its static and dynamic performance directly affects the machining accuracy of the machine tool [8].

To analyze the static behavior of the base we have used highly accurate FEA software from Altair -Hyper works to analyze the static and dynamic modes of the original model respectively, and find out the weak parts of the base, which provides the direction for optimization. 3DTetra element size ranging from 8mm to 20mm used for meshing and applied on Base for its all required FE Analysis iterations. The properties of Base materials are shown in Table 2.

Table 2. Base material properties

Material	Density (kg/m3)	Poisson's ratio	Tensile strength (Mpa)
Grey cast iron	7200	0.26	250

B. Malleswara Swami &, K. Sunil Ratna Kumar [2] has done study on Design and structural analysis of CNC vertical milling machine bed with different cast iron material grades. This study taken as reference.

This design mainly analyses the deflection, rigidity, and natural frequency of the base. Static analysis results are obtained by adding loads and applying boundary conditions according to working conditions [4].

Analysis methodology related inputs taken from similar work done for CNC turning center bed [7].

The component's deflection and stress response were investigated by applying four different mass loadings in successive iterations:

- Only base structure mass
- Machine X-Y axis in center positions

- Machine Y axis in center positions and X axis in end positions
- Machine X axis in center positions and Y axis in end positions
- Machine X-Y axis in end positions
- Machine X-Y axis in end positions as well as headstock assembly, column, and ATC mass. This is an Extreme condition to compare the results.

Table 3. Boundary conditions for FEA for new base compared to old base

Parameter	Values for old base	Conditions for new base values must be
Input loading condition-lumped mass	3500N	=
Maximum deflection	51µ	≤
Weight of the base	1387kg	≤

Must be = Equal, more > or Less < as compared to old base.

As stiffness is inversely proportionate to deflection according to following equation.

$$k = F / \delta \qquad (1)$$

Where
k = stiffness (N/mm)
F = applied force (N)
δ = extension, deflection (mm)

Here Static as well as dynamic frequency of the machine improved by reducing mass (weight) and by increasing stiffness concerning old design.

The general formula for frequency is:

$$f=(1/2\pi) * (\sqrt{k/m}) \qquad (2)$$

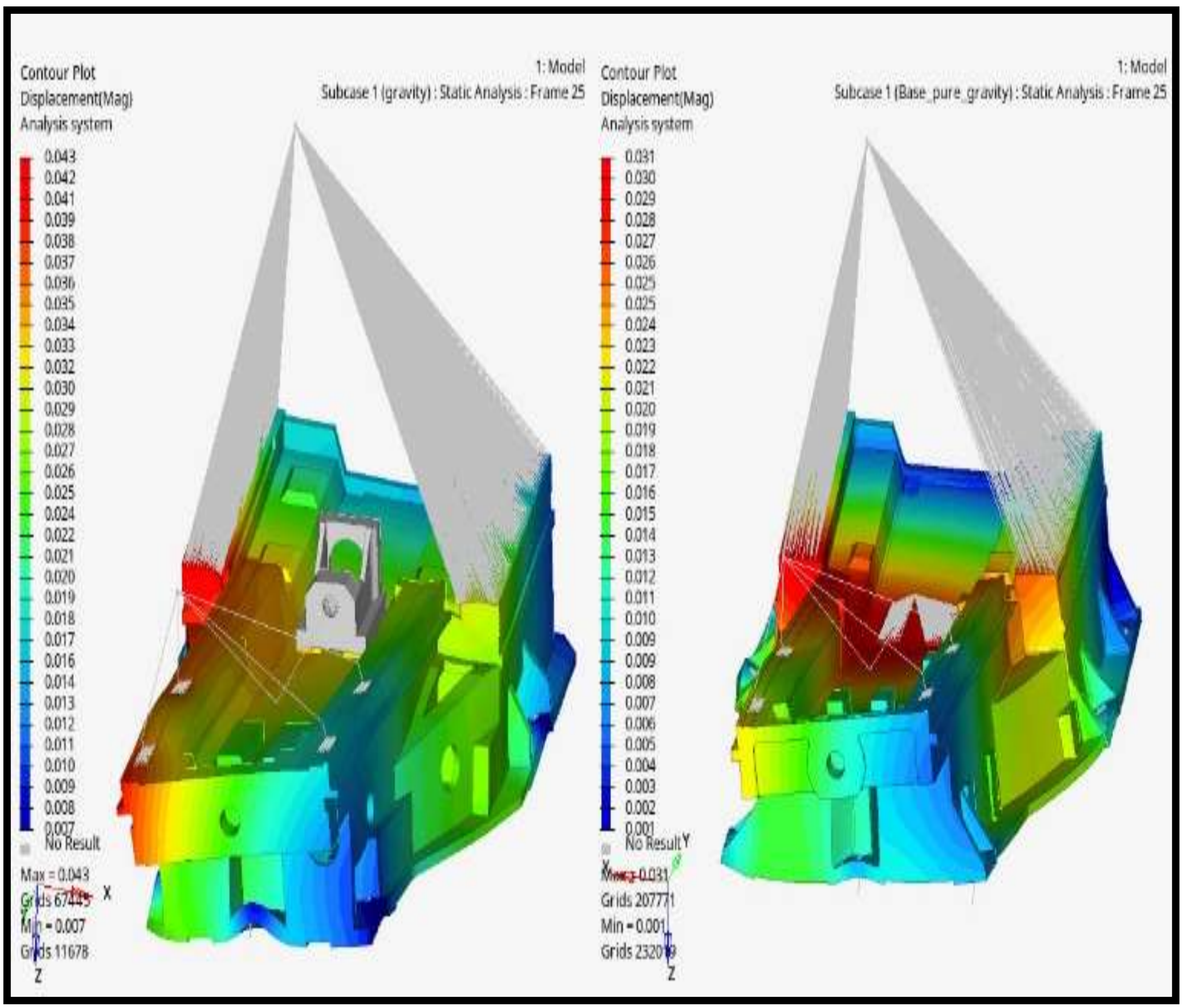

Figure 5. FEA analysis of old and new base design on Altair Hyper works 2022.2

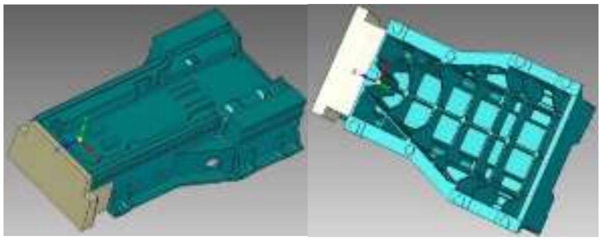

Figure 6. New base pattern design bottom and top view (Different colors shows different cores)

Figure 7. New base structure actual photo bottom and top view

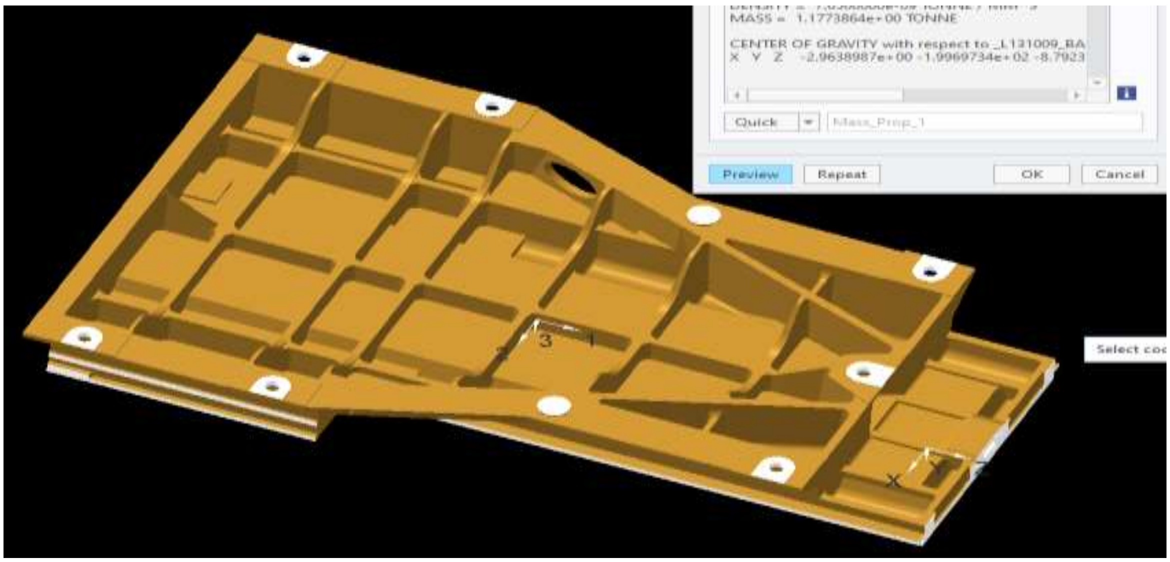

Figure 8. New base structure weight verified practically

6. Results & Conclusions

All the results mentioned is verified practically and this new design is now standardized in production at Jyoti CNC automations limited and old base is phased out.

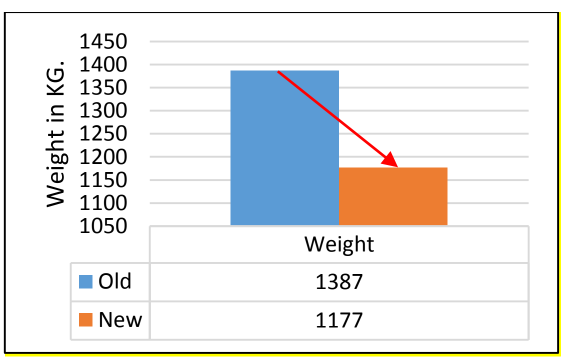

Figure 9. Wight old vs. new base

6.1 Weight reduction: The total weight of the base structure is reduced by 15%. This reduction can lead to cost savings, especially in terms of material costs and transportation costs. Additionally, it may contribute to improved machine performance and energy efficiency.

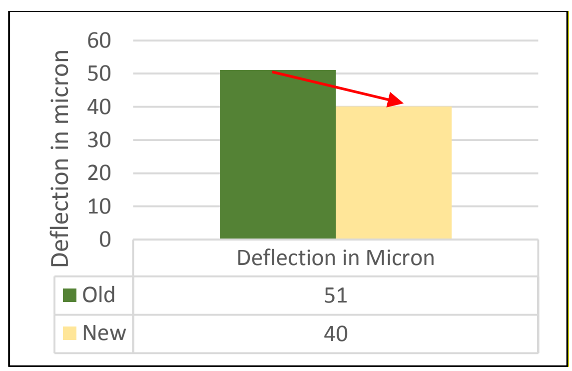

Figure 10. Deflection old vs. new base

Table 4. All parameters improved

Parameter	Improvement
Weight reduction	15%
Deflection reduced	20%
Core manufacturing time	22%
Core coating time	25%
Core setting time	80%
Part fettling time	75%
Total throughput time reduction	50%
Manufacturing cost reduction	45%

6.2 Deflection reduction: Total deflection is reduced by around 20%. This improvement is crucial for maintaining machining precision and ensuring the structural integrity of the machine during operation.

6.3 Core manufacturing time reduction: Core manufacturing time is reduced by 22%. Base Casting Manufacturing is made much easier with optimized design as redesigning the base with only a single core. This reduction is likely achieved through optimized design and manufacturing processes, contributing to overall efficiency in production.

6.4 Core coating and setting time reduction: One of the main benefits of our new core coating technology is that it reduces the time required to apply the coating to the core 25%.and core setting time is reduced by a substantial 80%. These reductions in core-related processes can significantly enhance production efficiency and reduce the overall manufacturing cycle time.

6.5 Part fettling time reduction: Part-fettling time is reduced by 75%. Fettling involves the removal of excess material or imperfections from castings. The reduction in fettling time indicates improved casting accuracy and less manual intervention in post-processing.

6.6 Total throughput time reduction and part accuracy improvement: Total throughput time and part accuracy are improved significantly. This is a crucial outcome for meeting production deadlines, improving overall efficiency, and ensuring the quality of the final machined parts.

6.7 Reduction in raw material usage: The optimization efforts have led to a reduction in raw material usage, including sand, metal, bonding material, and pattern material. This not only contributes to cost savings but also aligns with sustainable manufacturing practices.

6.8 Reduced error in core setting: Less human involvement in the core setting reduces the likelihood of errors, improving the overall reliability and consistency of the manufacturing process.

6.9 Reduced manufacturing cost: The significant weight reduction contributes to a considerable reduction in the manufacturing cost of the structure. This includes savings in material costs, process costs, labor costs, machining costs, running costs, and more.

In summary, the optimization efforts have not only led to improvements in the performance and efficiency of the machining center but have also resulted in substantial cost savings across various aspects of the manufacturing process. These outcomes underscore the value of advanced design and optimization techniques in modern manufacturing.

Acknowledgement

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