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The Deformation of Wax patterns and Castings in Investment Casting Technology

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Abstract

The dimensional accuracy of a final casting of Inconel 738 LC alloy is affected by many aspects. One of them is the choice of method and time of cooling the wax model for precision investment casting. The main objective of this work was to study the initial deformation of the complex shape of a rotor blades casting. Various approaches have been tested for cooling a wax pattern. When wax models are air cooled and without clamping in the jig for cooling, deviations from the ideal shape of the casting are very noticeable (up to 8 mm) and most are in extreme positions of the model. When the blade is cooled in the fixing jig in a water environment, the resulting deviations compared to those of air cooling are significantly larger, sometimes up to 10 mm. This itself does not mean that the final shape of the casting is dimensionally more accurate with the usage of wax models, which have smaller deviations from the ideal position. Another deformation occurs when the shell mould is produced around the wax pattern and further deformations emerge while cooling the blade casting. This paper demonstrates the first steps in describing the complex process of deformations occurring in Inconel alloy blades produced with investment casting technology by comparing results of thermal imagery, simulations in foundry simulation software ProCAST 2010, and measurements from a CNC scanning system using a Carl Zeiss MC 850. Conclusions are so far not groundbreaking, but it seems that deformations of the wax pattern and deformations of the castings do in some cases cancel each other by having opposite directions. Describing the whole process of deformations will help increase the precision of blade castings so that the models at the beginning and the blades in the end are the same.

Keywords: Application of information technology to the foundry industry; Innovative foundry technologies and materials; Investment casting; Wax patterns

1. Introduction

Investment casting allows the production of castings with complex shapes, small dimensional tolerances, and excellent surface quality. The great advantage of investment casting is the ability to produce castings from materials difficult to machine. Using a different technology would result in high costs, or production would be impossible. In comparison to machining, the dimensional accuracy of castings produced by precision casting cannot be compared, even though when compared with other methods of casting it is very accurate (IT 9 to 11). Of course, even with such perfect and precise production, dimensional inaccuracies occur for various reasons. The actual dimensional inaccuracies are divided into:

- systematic – i.e. poor handling of castings or incorrect assembly of the wax model. These defects can be eliminated by more carefully following the prescribed technology.
- random - difficult or almost impossible to remove defects.

Another factor that influences the size and characteristics of the wax model and casting is deformation. It occurs especially in parts that don't have a constant wall thickness.

The main factors affecting the dimensional accuracy of investment castings:

- volume expansion (contraction) – the main influence being the materials used - wax, shell material and casting material. considerable influence has as well The precision of the wax model molds also has a considerable influence.
- deformation of the wax models - cooling of the wax model and its further processing and storage have a major influence.
- shell deformation - the composition of the layers, the method of smelting the wax model, and firing and flushing of the shells.
- deformation of the casting itself - the shape of the casting and gating system, the shell temperature, pouring temperature, and if used, forms of isolation.

2. Dimension changes

The most important influence on dimensional accuracy of the final casting is the wax model itself. The final size of wax models can be changed by changing the parameters at which wax is injected into the mother mold; this method is practically the only possible way of influencing dimensional accuracy.
The achieved tolerance is determined by the following:

- wax mixture - increasing injection temperature increases shrinkage of the models. The structure and chemical composition of the wax mixture has an influence on expansion and contraction. The course of contraction or expansion in the temperature interval is not linear.
- shape and size of components - the value of shrinkage in different basic planes depends not only on the shape and size of component, but also on the placing of inlet part.
- method of producing the wax model - this includes both the injection of wax into the mother mold and the injection parameters.

2.1. Changes in shell dimensions

Changes in the shell during drying and annealing are defined primarily by the type of ceramic (granules and binders) used, the number of shell layers, the method of shell heat treatment (drying, rinsing and annealing), and the technology used in smelting the wax mixture.

The fact that cannot be ignored is that the shell expands during annealing. Here, the size of the shell expansion depends directly on the ceramic filling used, or to be more precise, on the coefficient of expansion. The number of layers, in which the wax model is encased also have an effect on dimensional changes. It is also possible that the shell can shrink rather than expand.. Shrinkage is moderate (up to 0.4%). The biggest influence on this contraction is the binder while drying.

2.2. Deformations of wax models

The main disadvantage of using wax models is that immediately after removing the injected model from the mold its components begin to deform due to the uneven temperature field. It is not possible to remove the wax model from the form at low temperatures because the wax gets very sticky at low temperatures, and the model would have to be crushed to be removed from the mold; similarly, the model cannot be removed while in a non-solid state. The main problem is that if in the model there are varying wall thicknesses, e.g. –a thin blade shape and a massive lock, could not be in a solid state at the time of removal.. Among the ways of slowing deformation is the almost immediate consolidation of the extracted wax model into the jig, where the ideal shape is defined. This method is also known as "braked hardening".

The resulting deformation of wax models is highly undesirable because they affect the quality of the final casting and cause significant inaccuracies in it.

To avoid distortion of the wax model in investment casting , cooling jigs are used after removing the model from mold, or in the case of a very large wax model, several jigs can be used (see Figure 1). If the final shape of the casting has non-uniform wall thicknesses and shapes, different parts of the model will neither cool nor shrink at the same time. Non-simultaneous cooling of different places in the model causes different parts of the model to change dimensions, and as a result, so-called stress or deformation appears.
Types of tension in wax models:

- phase tension - when combining two elements of different thicknesses in one unit, the tension is balancing differences of deformation of structures. Two kinds of stress arise. Tensile stress develops in the thinner walls, while compressive stress develops in the thicker walls.
- shrinking tension - another distortion occurs when the mold resists against shrinkage. The emergence of shrinkage depends on the shape of the model. The form is absolutely rigid (usually aluminum alloy or steel).
- heat stress - this tension arises when two bodies with varying wall thicknesses are connected but at the same temperature. This type of stress causes deformation. The profile with the thin wall cools down before the profile with the thick wall. The thinner wall is stronger and resists shrinking at the other wall, which has a greater thickness. All this leads to shape deformation in the wax model. The greater the differences in thickness, the higher the stress (deformation).

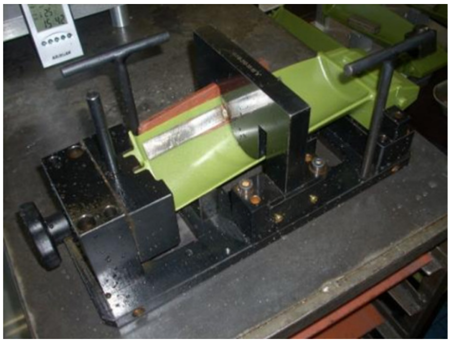

Fig. 1. Wax model of blade fixed in jig

3. Checking the shape of the impeller blades

As stated in the previous paragraph, castings produced using investment casting technology are ultimately influenced by deformations in the wax pattern and ceramic mold. To evaluate the magnitude of inaccuracies in the dimensions of the blade wax pattern and on the subsequent casting of the blade, a series of measurements had to be taken. Analysis was carried out using the Carl Zeiss MC 850 coordinate measuring machine.

This machine is equipped with an active scanning system (Vast XT 2.1 Scanning System).

The analysis was performed using a contact measurement with a fixed sensoring system. This means that the system does not allow the positioning of the measuring sensor. In order to measure all the required elements a special configuration of sensors (measuring probes) was built. To measure the horizontal cut direction + Y and -Y ball touch probes with a diameter of 3 mm were selected. For measuring cylindrical risers (used for alignment) in direction + X and-X, ball touch probes with a diameter of 1.5 mm were chosen. And for measuring the vertical cut in the direction -Z, a ball touch probe with a diameter of 3mm was selected. After building of the configuration sensors, it was necessary to classify this configuration, i.e. determine the location of the measurement touch probes relative to a reference sensor. This classification is carried out using a calibration norm which in this case was a sphere. When measuring, it is necessary that the part is fixed with sufficient rigidity so it does not move or deflect during measurement. Fixing had to be done in such a way that it could perform measurements in a single setup. The blade was fastened at the bottom lock part where the fastening lock into the impeller will be machined. The components of this type are generally offset by RPS (Referenz Punkte System) where the principal coordinate system of the machine (in this case a whole gas turbine) is transferred using RPS point to the individual part (i.e. blade) and thus can then be measured to evaluate the main part of the coordinate system of the whole machine.

In the first step, due to shrinkage of the Inconel alloy, the wax models of the blades were measured and found to be 2.9% larger . By making the wax models larger, the RPS method could not be used because the measuring software is unable to compute the alignment of the component in such conditions. For the alignment, the classical method was used plane - line - point (3-2-1), the shaped area located at the bottom of the blades was used.

In the second step, the Inconel blade castings were measured. In this case it would be possible to use RPS alignment, but to have the same conditions as in the measurement of the wax models, plane - line - point alignment was again used.

To measure the shape of the blade, a 3D model was used, and 7 cuts were defined. 6 horizontal cuts in the Z = 8o, 120, 160, 200, 240, 265 mm and a vertical cut located in the center of the blade. Approximately 190 to 250 points were placed at horizontal sections depending on the length and curvature of each specific cut. Measuring these cuts with a single sensor could not be done, so they were divided into two parts, and the sensors measured + Y and -Y. The points on the leading edges (the curves between these parts) were not measured because edges are rough, and to evaluate these points was irrelevant. The vertical section includes 70 points and was measured by sensor -Z.

All sections (cuts) were measured in a scanning manner, i.e. the probe was pressed against the surface with a constant force and measured the points continuously while moving. This method is much more productive than measuring individual points. All the measurements were carried out in CNC mode. The obtained results were evaluated in two ways: graphical protocol and 3D model.

In order to get a detailed idea about the shape of the blades, each slice was evaluated separately in a graphic log (Fig. 2). These protocols show variations in the defined measuring points from the ideal shape represented by the 3D model. The black curve shows the shape of the cut obtained from the 3D model. The green color shows positive deviations leading from the material and the red negative leading towards the material. The blue curve is the envelope of the measured deviations. The scale is 20:1.

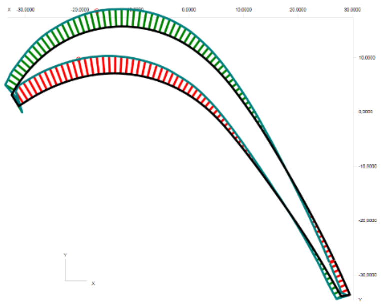

Fig. 2. Cut out from graphics protocol 3D visualization

As a better idea, the graphic evaluation was created directly to the CAD model in the measuring software (Fig. 2.4).The size and direction of the deviation could then be seen in 3D view and created a better idea of deformations of the functional parts of blades. The scale of the measured deviations was 7:1.

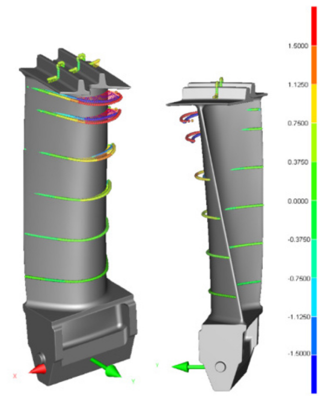

Fig. 3. Measured differences in dimensions shown on 3D model

4. Simulations of the cooling processes

To reduce the need for casting a series of verification castings whenever any technological process change was proposed, foundry simulation software ProCAST 2010 was used. Due to the enormous breadth of parameters available in the ProCAST software, it was possible to use it to simulate the solidification of the wax models, as well as for castings from Inconel 738 LC alloy.

ProCAST simulation software is based on FEM calculations, thus the first step was to create 3D models of all the simulated components. The second step was to create a tetragonal mesh on the models. And the third step was to set all the parameters of casting and solidification exactly as in the real process. Then we could start the calculations, and all that remained was to evaluate the results.

For the purposes of our simulations it was necessary to create models of the blade and its cooling jig. A 3D model was based on original drawings of the blade and the models used to create the wax injection molds. The model of the cooling jig was based on measurements of the currently used equipment. The blade model, when compared to the actual casting, had several simplifications, such as removing labels, removal of minor bumps, etc. The model of the jig was completely faithful in bearing surfaces and all dimensions which fixes the blade, but in all shape details that are not important for accurate simulation were simplified to basic shapes. The bearing area was shared by the blade and jig, thus presuming an idealized situation where the blade fits perfectly into the jig.

When the models were done, they were converted into tetragonal mesh for further computations. After creating a surface mesh it was necessary to thoroughly check the entire surface mesh on the models and any errors must have been corrected so that the mesh had the required parameters of triangles. This means removing very small angles at the vertices and correcting small triangles emerging on the contacts of areas. After correcting the surface mesh, several resulting tetragonal meshes for thermo-mechanical calculations in the ProCAST simulation software were created. A complicating factor was that it was necessary to maintain the numbering of nodes in each case setting, i.e. the actual blade model from wax, wax blade in the jig, and blade casting from the Inconel 738 LC alloy. This was due to the fact that the results of mechanical stress and the deformation of the individual steps of the simulation are then loaded as initial conditions for the next step. To optimize the computations, different mesh density was used in different places of the model so that important areas preserved details. The resulting tetragonal mesh had 5.3 million elements.

Obviously, the simulation is trying to copy the physical process of solidification, i.e. in each step ProCAST software options were used to load as the default state of deformation and stress in the casting results from previous simulations. Simulation steps that needed to be followed were the following:

- injected wax solidification in metal mold,
- free cooling of wax blade on the air during the fixing in jig,
- final cooling of wax blade fixed in jig in the water,
- free cooling of wax model stored in the warehouse,
- the solidification of blade casting from Inconel 738 LC.

In this early stage of research, a general model of foundry wax, as defined in the ProCAST software, was used for the blade simulations. This wax is clearly not entirely consistent with the wax used in production; therefore, it was necessary for further research to fully define the real material used which would have coincided with the thermomechanical properties of the real wax material. Unfortunately, knowledge of the parameters for waxes is generally very small and available tabulated values, as available in metals and metal alloys, cannot be used. Necessary data is unable to provide the manufacturer of the wax, so at this stage of research the measurements of the physical parameters needed are taken in the laboratories at the Faculty of Mechanical Engineering, CTU in Prague. So far, about one half of all needed properties were measured and described. Input data are mostly temperature related function of property, i.e. density related to temperature. Temperature range must cover all values needed for simulations, so from room temperature 20°C to 80°C which is enough above liquidus. Properties needed for complete simulation were the following:

- thermal conductivity λ (W/m/K),
- density ρ (g/cm^3),
- specific heat c (kJ/kg/K),
- Young's modulus E (MPa),
- Poisson's ratio ν,
- thermal expansion α (1/°C),
- shear modulus constant and relaxation (time dependent) (kPa).

So far, thermomechanical properties were measured. Example of the obtained data for density is given in Fig. 4.

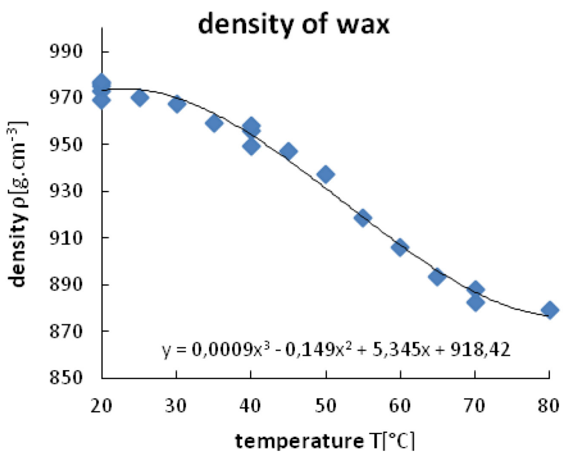

Fig. 4. Density of model wax related to temperature

The simulation itself is completely autonomous, and the only requirement, which in this case arose, was considerable computing power. Calculations were carried out on a computer workstation equipped with a 6 core AMD 1100T (6 x 3.4GHz) and 16GB RAM. Because the models used had very fine mesh in order to achieve accurate results, the simulation took tens of hours each.

After removing all the errors in the process simulation, the results were obtained for the temperature field, the distribution of liquid and solid phase for both wax and Inconel 738 LC alloy, stress and strain fields on all parts and in all steps. Direct comparison of results from simulations and the measured data showed that results are of the same order, and in terms of strain amplitude, without exception, were deformed in the same direction in both the simulation and the real case. However, the simulations showed the absolute amplitude of deformation greater than in the real case, which so far can be blamed on the use of general wax as the material in the simulation. After obtaining the necessary data on the thermomechanical wax used, the entire simulation will be repeated and again evaluated.

Cutout of the overall deformation vector results at z=160mm is presented in fig. 5. This situation should be comparable to the one presented at fig. 2.

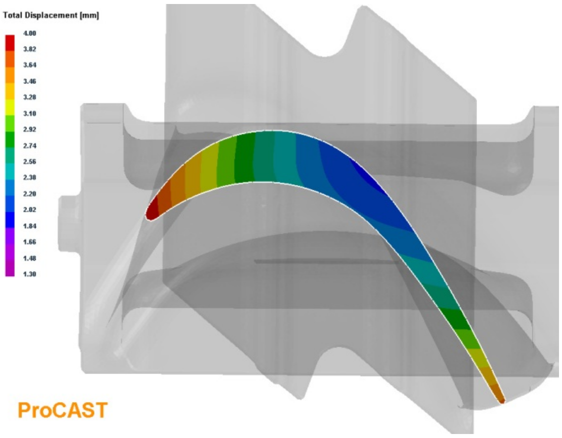

Fig. 5. Total deformation vector of wax pattern at z=160mm

To verify how accurate the simulations were, it was decided to use a thermal camera to capture the entire process of making the wax pattern of the blade and to compare the results. The processed picture of the wax blade just removed from the mould is shown in fig. 6. The same situation from results of the simulation are shown in fig. 7. The results differ only about 2°C in both min a max value.

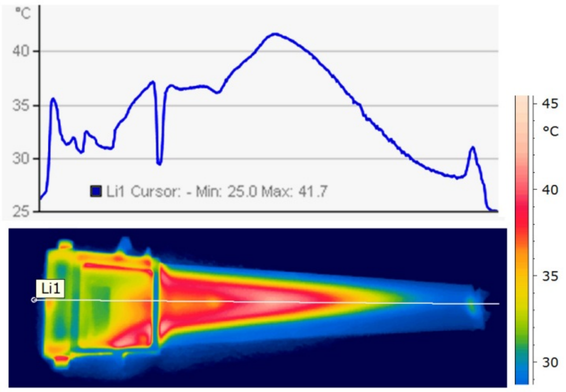

Fig. 6. Wax blade just removed from mould, thermal image

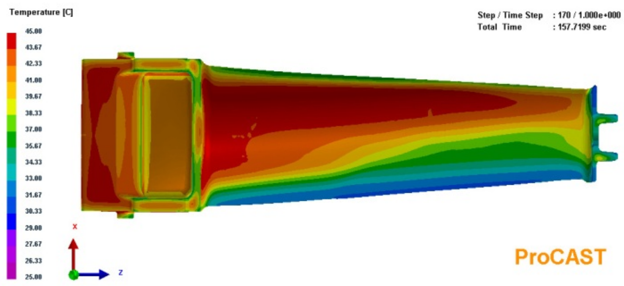

Fig. 7. Wax blade just removed from mould, simulation

5. Discussion of results

The experimental work so far consisted of three main parts: production of the wax patterns, ceramic mould and casting the blade itself, measuring the dimensions of the blade, and simulating the whole process virtually.

The entire process of making the wax patterns and casting the Inconel blade was documented using a thermal camera. Resulting thermograms revealed huge differences in temperatures of different parts of the blade wax pattern. So far, the production process used was as follows:

- injecting wax into the mould 150 sec delay for cooling;
- removing and fixing in jig, placed in 18°C water for 420 sec;
- storing in thermal stable storage at 22°C.

Deformations after this process exceeded almost 10mm in z=160mm measured from side of the blade lock (Fig. 8).
The casting produced from this wax pattern was also measured and maximal deformation occurred in z=265mm which is the last possible cut just before the upper blade lock (Fig. 9) and exceeded 6mm. From detailed study of the deformations of all measured cross-sections on both the wax pattern and succeeding castings, it is evident that both deform mostly in the same manner (i.e. direction), but since casting deformations have a lower amplitude, the casting deformation has the opposite direction from the deformation of the wax pattern. The same conclusions were obtained by the simulations in the ProCAST 2010 software but with much greater differences in amplitude.

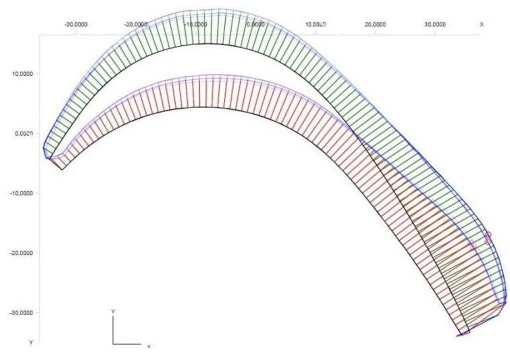

Fig. 8. Measured deformations of wax pattern at z=160mm

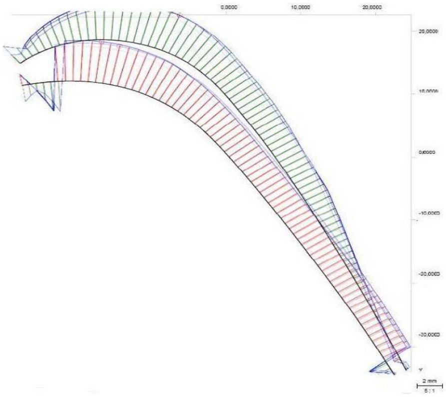

Fig. 9. Measured deformations of casting at z=265mm

6. Conclusion

The dimensional accuracy of the final casting from nickel Inconel 738 LC alloy is affected by many aspects. One of them is the choice of method and time of wax model cooling for precision investment casting.

When wax models are air cooled, without clamping in jig for cooling, deviations from the ideal shape of the casting are very noticeable (up to 8 mm), and most noticeable are deviations in extreme positions of the model. For cooling blade models in the cooling medium, water at 18 ° C was used. The actual model was still clamped in the fixing jig to define its position and shape. Cooling lasted for 7 minutes. The resulting deviations compared with air cooling are significantly larger, sometimes up to 10 mm. This itself does not mean that the final shape of the casting is dimensionally more accurate when using wax models, which have smaller deviations from ideal position. It is possible that these deformations in models are required and caused while smelting casting molds. The resulting cooling of the casting gets to its ideal shape by shape changes during its cooling.

The relatively large deviations from the ideal position can be caused by inaccurate temperature of water used for cooling the models, and respectively, higher air temperature at the cooling place. Another factor influencing the inaccuracy of these dimensions is the careless handling of wax models that are not yet completely solid. Human error must also be included since poor handling could also end up in inaccurate clamping of the model in the jig for cooling under water. The temperature at cooling storage was 22 ° C and the temperature of the car used to transport wax models of blades to measuring was to 35 ° C, so it is possible that this adverse change in temperature has influence on the final deformation.

By comparing the simulation results obtained using ProCAST and the measured values of the coordinate measuring machine MC 850, it is concluded that the deviation of wax models of blades from the ideal shape in these intervals are in a tolerable range; since the simulation of cooling wax models was considering to be ideal conditions, deviations shown in the simulation are up to a few small inaccuracies (0.1-1 mm) almost the same.

For the final casting of the blades from Inconel 738 LC alloy, simulations using the ProCAST software was also performed. The remeasurement of the castings, where the wax model cooled in water and in the jig, showed that the smallest deviations from the ideal shape were in the section closest to the beginning of the Z axis; and vice versa, the largest deviations were in the cut farthest from the beginning of the Z axis.

From the analysis of results of the measured blades casts using the wax model cooled in air at 22 ° C, it can be concluded that in this case deviations are the smallest in the cut, which is near the beginning of the Z axis, and vice versa the largest was in the cut located furthest from the beginning of coordinates.

To summarize the knowledge that we gained by measuring the blade, we can specify that in some sections, the blade deforms almost the same as the wax models. It is also evident that the whole profile of the blade is shifted. This could mean that the blade casting does not deform at cooling, but is deflected in the Z axis without unwanted twisting.

However, if the setting of the coordinate system worked correctly, it means that the deformations of the blade casting are undesirable and should be avoided. This can be achieved by spreading the pressure acting on the wax model surface in the cooling jig on more cross sections. This means that instead of defining the current position in the three sections it is preferable to fix the blade in the jig, e.g. at five locations.

Another task for further research is to obtain more accurate thermo-physical and stress-strain data of used wax mixtures for obtaining truly accurate results from simulations.

Acknowledgement

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