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Research Article

Simulation of Ni-Based Super-Alloy and Optimizing of Its Mechanical Properties in a Near-Shaped Turbine Blade Part

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This paper presents simulation of a Ni-based super-alloy during filling of a near-shaped turbine blade part to optimize its mechanical properties. Since geometrical shape of the airfoil is so complicated, a simple near-shaped part was made by plexiglass to water modeling. Condition and parameters of water modeling were obtained from the Procast software simulation. The flow pattern of the transparent systems, recorded by a high speed video camera, was analyzed. Air bubble amounts were quantitatively measured by an image analysis software. Quantified results were used to compare two systems in terms of ability to prevent bubble formation and entrainment. Both water modeling and computer simulating methods indicated that highest turbulences in bottom- and top-poured systems form in first initially pouring times. According to the water modeling results amount of bubble values was 40 and 18 percent for top-poured and bottom-poured systems, respectively. Then the Ni-base super-alloy IN939 is poured by investment casting in bottom- and top-poured systems and compared with each other. The results stated that bottom-poured system had higher mechanical properties compared to top-poured one. Ultimate tensile strength for the former was 820 MPa while for the part which was cast by bottom-poured system it was 850 MPa.

1. Introduction

Nickel-based super-alloys are generally used for the production of high-performance turbines for power generation. The requirements for near-net shape, accuracy, and surface finish dictate that the blades are cast in investment molds in a vacuum furnace. However, because of the necessity for the investment wax assembly to be robust, many investment castings use top-poured gating systems. This undesirable filling technique introduces the danger of the random entrainment of the surface of the liquid metal into the bulk of the casting. Despite the use of the vacuum for melting and casting, there is, of course, plenty of residual air in the vacuum environment to ensure that a surface film of oxide or nitride will form. During the turbulence of the pour, it is to be expected, therefore, that oxides and, possibly, nitride surface films will be formed on the falling liquid [1–4].

In addition, surface turbulences of melt flow caused by flow velocities, greater than the critical value of 0.5 m/s, were known as the only mechanism for the formation of the oxide defects in most of the alloys. But it was shown by Campbell that passing of the air bubbles through melt leads to the formation of special kind of oxide defects, named “bubble trail.” Each bubble trail is an oxide tube formed at the premier of an air bubble and then is crumpled by the melt pressure. The sequences of formation of a bubble trail, as well as its cross section at different heights, are shown in Figure 1. These oxide trails have a high potential to get trapped in the solidified casting and may provide a leak path across the wall, deteriorating the expected performance. Gravity casting of metal alloys consists of flow of molten metal through a channel with varying height, namely, the gating system. The change in flow velocity due to these varying heights and cross section areas, as well as the nature of pouring the melt from ladle to crucible into the entrance of the gating system, results in flow turbulences and entrapment of air bubbles, which finally lead to formation of bifilms and bubble trail. So there has been a lot of work trying to optimize the gating system in a way that less flow turbulences and bubble entrapment are achieved [5–7].

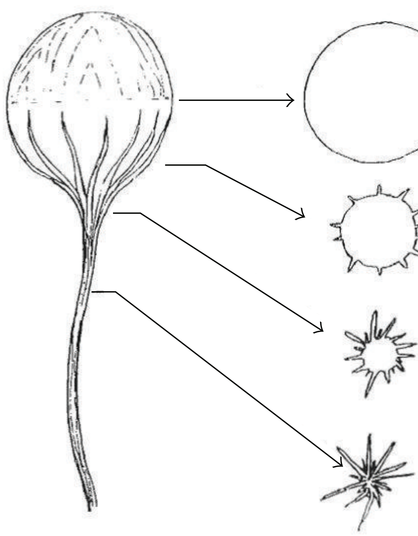

Figure 1: Formation of bubble trail and its cross sections along the length [5].

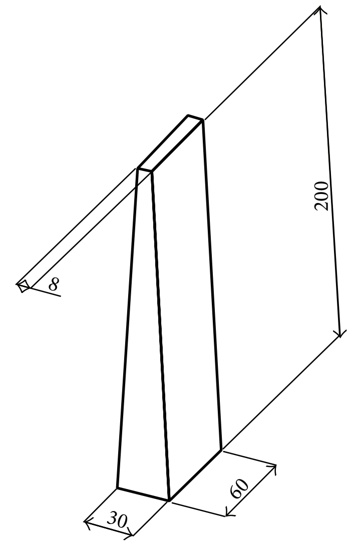

Figure 2: The schematic of the mold made by plexiglass (dimensions are in millimeters).

Therefore, gating system plays a very important role in foundry practice, since it is the only entrance for molten metal to fill the mold cavity. Furthermore, a good gating system is not only an entrance, but it also functions in many ways as a key link in quality control of casting production. It has to take the burden to control the metal flow passing through it. Therefore, gating system design is always an important topic in foundries [8–10].

In investment foundries, it is usual to pay relatively little attention to the design of the filling system of a casting. Vacuum-cast turbine blades represent a typical case, where the mold filling process is poorly controlled, the mold cavities themselves often being top-filled. The consequential surface turbulence causes the entrapment of oxide film on the liquid surface, despite the use of vacuum melting and pouring. Investment casting in vacuum is the accepted standard processing route for the manufacture of turbine blades and nozzle guide vanes in Ni-based super-alloys. Considerable literature is available concerning the effect of alloying elements and processing variables on the high temperature mechanical performance and oxidation resistance of these products. However, data on the influence of the filling system is meager [11–14].

2. Experimental Method

In water modeling, doing experimental models, certain mechanical similarities have to be fulfilled. To get dynamical similarity the force ratio has to be kept. The Froud number has been kept by the identical geometry (scale 1 : 1). The kinematical viscosities of cast iron and water almost equal (is about $1.94 \times 10^{-6}\ \mathrm{m^2\ s^{-1}}$), so the Reynold number can be kept too [10].

Cast iron was considered to be a suitable alternative because it has similar density and surface tension and thus overall similar flow behavior to Ni-based alloys. In this paper, in order to investigate the effects of gating system on bubble entrapment phenomena during pouring and mold filling, two bottom- and top-poured systems for a near-shaped part were prepared. Then both systems were imaged successively while being filled with colorful water. After that, each image was subjected to computer image analysis and results were used to obtain graphs showing the amount of bubbles, which were used as a means to compare the efficiency of studied gating systems in preventing bubbles formation and their entrance into the mold cavity [13].

In this research, a piece made of plexiglass was used as a mold. The schematic shape and dimensions of the mold are shown in Figure 2. According to unpressurized gating system, a bottom-poured gating system for the mold was designed using Procast software simulation. This mold was also filled from the top as a top-poured system. These setups are shown in Figures 3(a) and 3(b).

Using simulation software, optimum flow rate value for bottom-poured system was achieved. Dimensions of gating system were calculated according to mass conservation rule and diagrams of cast iron. According to the calculations, the areas in upper part and lower part of the sprue were 177 and 77 $\mathrm{mm^2}$, respectively, and section areas of runner and gate were 150 and 300 $\mathrm{mm^2}$, respectively. In the bottom-poured system, pouring basin was big enough to reduce turbulences. For top-poured model, just a conical basin was designed. Then both systems made of plexiglass were assembled on a scaffold, and using a water tank, the flow of water was poured into the poring basin to model the poring process. Meanwhile, a Nikon D300 professional camera was used to take continuous pictures from the systems being filled with water, with approximately 5 shots per second.

In the next step, the bubbles in the mold area of each picture were selected. Then, by the help of ImageJ, an image

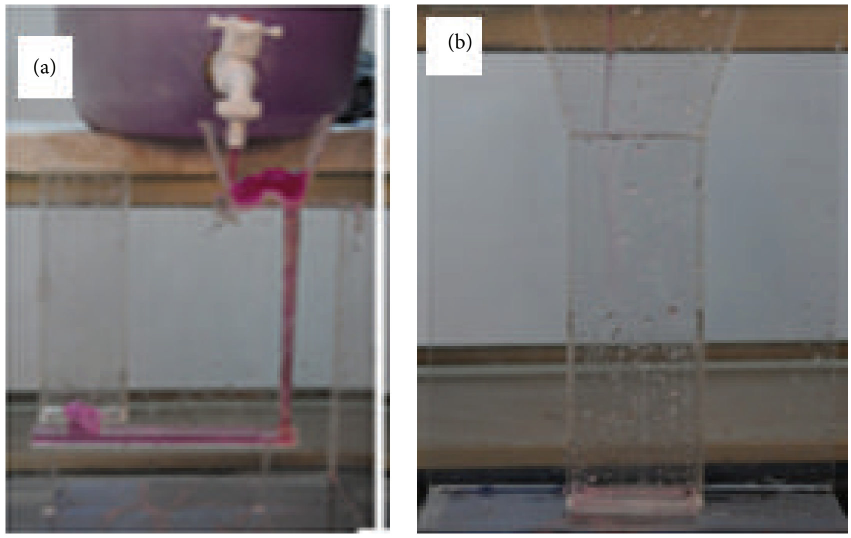

Figure 3: Setups of (a) bottom-poured and (b) top-poured systems.

analysis software, and also equation (1), percentage of the bubbles was estimated. Consider

$$\text{Mold fill\%} = \frac{\text{Mold fill volume}}{\text{Total mold volume}} * 100,$$
$$\text{Bubble\%} = \frac{\text{Bubbles are in image}}{\text{Area of the filled fraction of mold}} * 100. \quad (1)$$

Using these results, a plot was obtained for both systems, showing the percent of entrained bubbles in mold cavity versus mold fill percent. These plots show the changes of entrained bubbles during the mold filling and the area under the plots was a comparative measure of the total bubbles that entered the mold cavity during the filling. Based on these data, the effect of gating system and some other factors on the formation of air bubbles and their entrance into mold cavity were studied.

After that, according to the computer simulation a bottom-poured system was simulated for Ni-based superalloy IN939. Figures 4 and 5 show temperature and velocity profiles, respectively. Then two parts were cast by investment casting in vacuum atmosphere 10^{-3} bar. Chemical composition of the alloy is according to Table 1. Pouring temperature in casting and simulation processes was 1500°C and mold was preheated up to 1050°C.

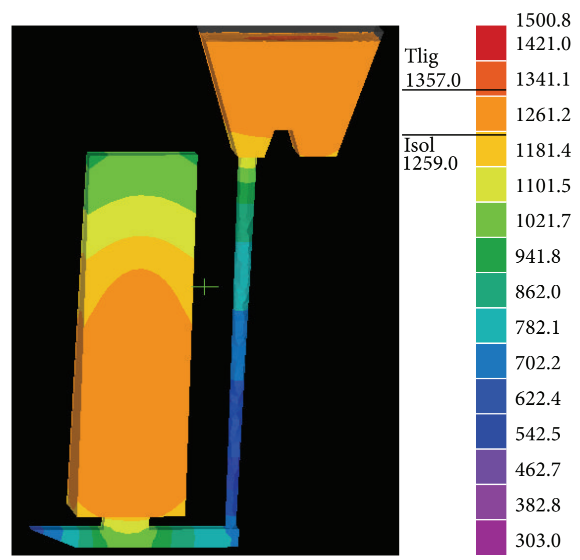

Figure 4: Temperature profile of computer simulation for IN939 in the mold.

3. Results

Pictures taken by high speed camera are shown in Figures 6(a) and 6(b). According to these figures, bubbles amount in top-poured system is higher than that in bottom-poured system. Gating system with tapered sprue leads to considerable reduction in the entrained bubbles, compared to the top-poured system. In top-poured system, the water falls from a high height and causes more turbulence, while in the other system, the water fills the mold from the lowest point of it and total turbulences decrease significantly. Figures 7(a) and 7(b) show the variations of entrained bubbles percent versus mold fill percent for both systems studied. The other behavior that is observed is the continuous reduction in bubbles present in the mold cavity as the mold is filled with water in both systems.

At the beginning of the pouring of bottom-poured system, the severe turbulence caused by the collision of the liquid with the basin results in a catastrophic air entrapment, and, again, as the pouring basin is empty this mixture of liquid and air enters the sprue within a fraction of a second. But as the time passes and the liquid level in the basin is elevated, the falling stream lands in a soft bed of liquid, which reduces the amount of entrained air and entrapped bubbles an after that,

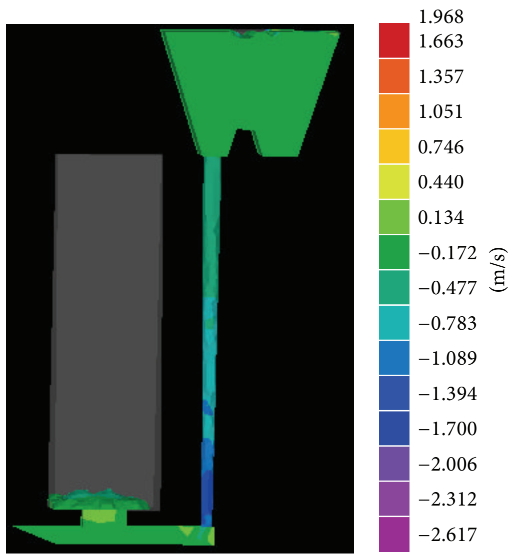

FIGURE 5: Velocity profile of computer simulation for IN939 in the mold.

TABLE 1: Chemical composition of IN939.

Chemical element	Percent element %
C	0.15
Si	0.01
Mn	0.02
P	0.005
S	0.003
Cr	22.4
Co	19.0
W	2.0
Nb	1.0
Ta	1.4
Al	1.9
Ti	3.7
B	0.009
Zr	0.01
Ni	Base

the liquid, along with the entrapped bubbles, stays in the basin for a longer time, enhancing the bubbles escape to surface. The highest amount of bubbles in both systems forms in first initially pouring times and its value is 40 and 18 percent for top-poured and bottom-poured systems, respectively.

Tensile properties were measured for two parts in two systems. And it concludes that the bottom-poured part has higher mechanical properties than the top-poured part. Table 2 shows the tensile properties of the two parts.

4. Discussion

Top filling of metal directly into the mold cavity is a very common practice used by the investment casting industry. It is more widespread than in other parts of the foundry industry, such as sand casting, where there is a trend to move away from top filling to bottom filling for high quality parts. Top filling means that a metal falls through the mold in the turbulence uncontrolled way and oxide films that form on the falling metal surfaces are entrained in the casting. Bottom filling has greater potential for less turbulence because the metal enters the mold through channels which are designed to introduce the metal in a controlled way into the lowest parts of casting cavity; thereafter the metal rises up in the mold with minimal turbulence [15, 16].

TABLE 2: Tensile properties of IN939 in the bottom-poured and top-poured systems.

System	Tensile strength Mpa	Yield strength MPa	Elongation %
Top	820	715	11
Bottom	850	730	10.6

The aim of this research is to compare the bottom-poured gating system with top-poured gating system in a simple near-shaped turbine blade via simulation. Air bubbles caused by the systems were also studied.

When the liquid stream falls in the pouring basin, the resulting turbulences cause the formation of the air bubbles. After a bubble is formed in the pouring basin, the buoyancy force, originating from the density difference between the air inside bubble and the liquid, tends to move the bubble upward. On the other hand, as the liquid in the basin is constantly flowing toward the sprue entrance and into it, the bubbles entrapped in the liquid bulk are also drawn to the direction, which probably includes a downward movement. So, if the upward buoyancy acceleration can overcome the downward flow velocity and viscous forces, the vertical component of bubble movement would be upward, leading to its escape from the liquid surface. Pouring basin and sprue design play an important role in determining the severity of bubbles formation and entrainment [5].

According to the above reasons maximum percentage of bubble formation for both systems was observed at the beginning of the pouring and its amount was 40 and 18 percent for top- and bottom-poured system, respectively. Therefore, gating system plays a very important role in foundry practice, since it is the only entrance for molten metal to fill the mold cavity. Furthermore, a good gating system is not only an entrance, but it also functions in many ways as a key link in quality control of casting production [9, 16, 17]. According to the computer simulation and investment casting for the IN939 alloy, mechanical properties were improved in the bottom-poured system.

5. Conclusion

Water modeling of the near-shaped turbine blade part indicated that bottom fill design with narrow section channels had great advantages. This system caused less air bubbles and better filling quality. In this system, air bubbles were rarely seen, while in the top-poured system they could be observed almost all around filling process. Maximum percentage of

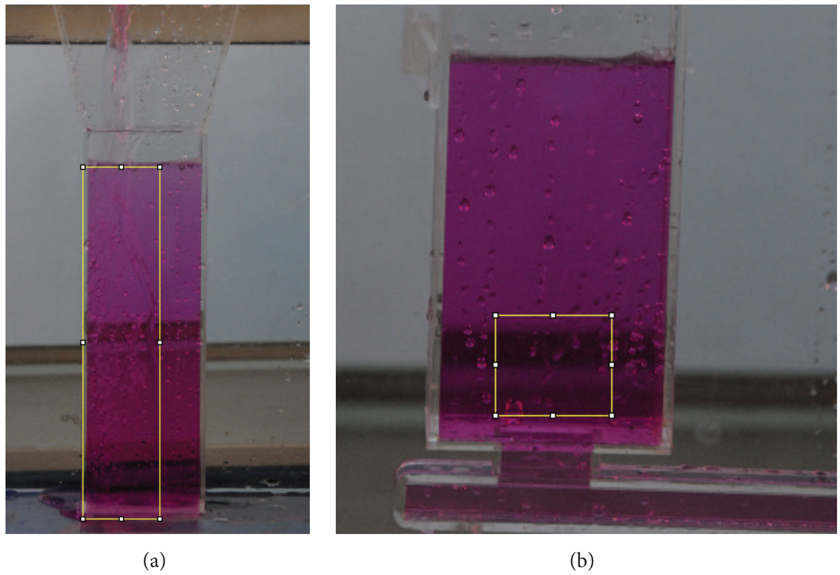

Figure 6: Bubbles in the (a) top-poured and (b) bottom-poured systems during filling.

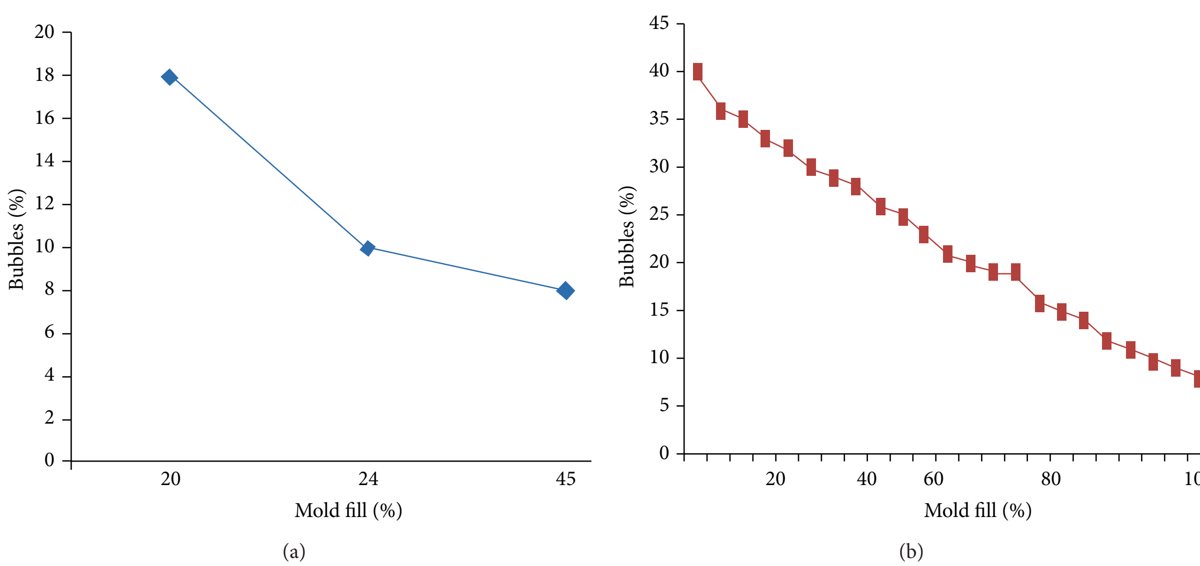

Figure 7: Variations of entrained bubbles during mold fill in the (a) bottom- and (b) top-poured systems.

bubble formation for both systems was observed at the beginning of the pouring and its amount was 40 and 18 percent for top- and bottom-poured system, respectively. In the bottom-poured system, at the beginning of the pouring of bottom-poured system, the severe turbulence caused by the collision of the liquid with the basin resulted in a catastrophic air entrapment, and, again, as the pouring basin is empty this mixture of liquid and air entered the sprue within a fraction of a second. Then as the time passed and the liquid level in the basin was elevated, the falling stream landed in a soft bed of liquid, which reduced the amount of entrained air and entrapped bubbles and after that, the liquid, along with the entrapped bubbles, stayed in the basin for a longer time, enhancing the bubbles escape to surface.

The simulations and investment casting results also indicate that higher mechanical properties are achieved by bottom-poured method.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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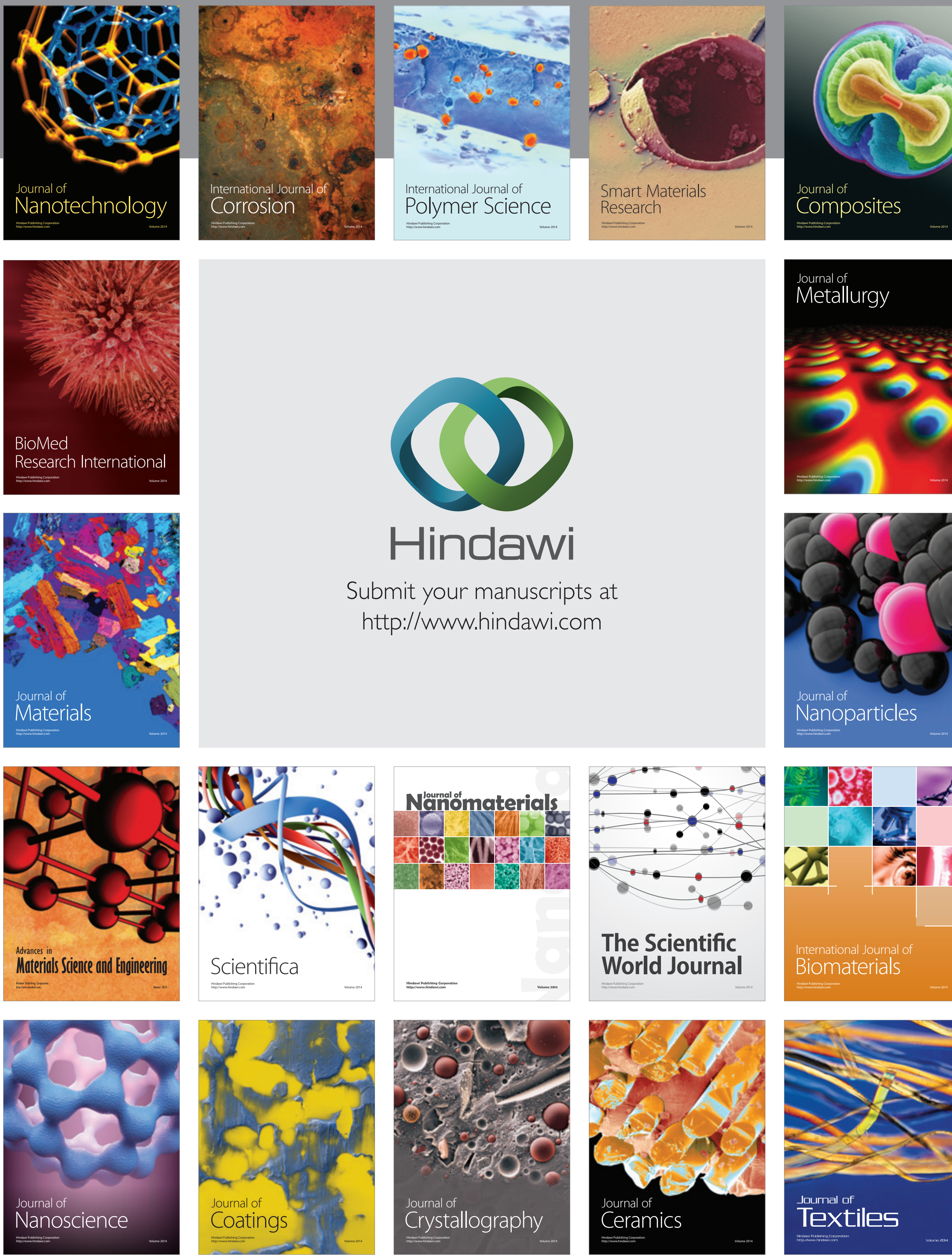

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