Development of blade forging by optimization of the material flow

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Abstract. The paper presents a practical case of forging technology development of turbine blades made of alloyed steels. It is based on optimisation of the material flow using the simulation software **QForm** and improvement of mechanical properties of the die surface. The simulation helped to find an optimal position of a profiled workpiece in preforming dies by altering the orientation of the blade's cross sections with respect to applied forging load. By means of coupled thermo-mechanical simulation in the system "tools-workpiece" it was also found that the temperature of preliminary die heating may have a significant influence on die life. Further extension of tool life was achieved by improving mechanical properties of die material by means of electric spark alloying. It provided not only coating of the die surface by hard material layer but penetration of the alloying elements to the depth of 0.2…0.3 mm. As a result of such complex approach the tool life for hot forging of the blades made of Ni alloyed steel has been increased from just few parts per die set up to 600 parts for upper die and to 1000 parts for lower die.

Keywords: Blade forging, Simulation, Optimization, Tool life

1. INTRODUCTION

The big part in total cost of gas-turbine engine production belongs to the cost of turbine blades. They are very complicated and critical parts of the engine and subject to mass production. The blades are difficult to forge because they have a thin long part, bulk lock part and made of heat resistant hard materials. The technological cycle includes also machining and heat treatment. This paper covers optimization of the technological sequence, proper selection of heating temperature and improvement of die material properties by electric spark alloying.

The turbine blades are produced in a crank press with dimensional allowance on the thin part of the blade 1.5…2 mm. The accuracy of the blade height should be within the limits 0.8 mm for the whole production batch.

The main factors that reduce the tool life during blade production are:

- Fracture failure due to overloading;
- Die wear;
- Plastic deformation of the die cavity.

The presented approaches for improvement of the tool life may be divided in two groups:

- Reduction of the forging load by changing the pattern of the material flow and sequence of the blows;
- Increasing of the physical and mechanical properties of the dies and die surface.

2. IMPROVEMENT OF THE MATERIAL FLOW DURING BLADE FORGING

The traditional blade forging technology includes several upsetting operations (usually from two to four) for accumulation required volume of the material in the head and forging this profiled billet in a crank press in 3…4 actions.

The typical sequence of the operations when producing the blade from nickel based alloy XH65BMTU (GOST) is shown in **Figure 1**.

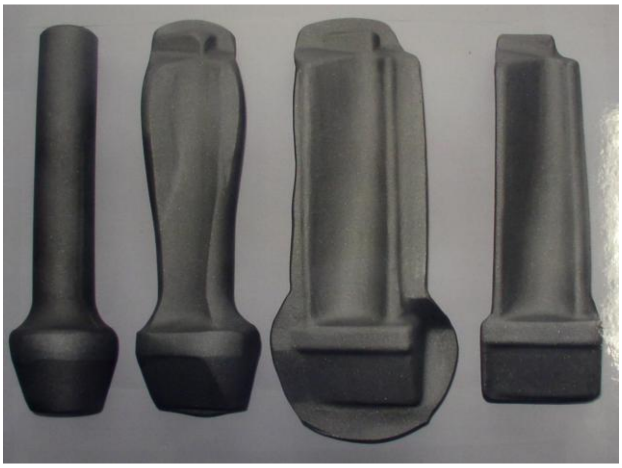


Figure 1. Sequence of the forging operations before optimisation: head upsetting, preliminary forging, finish forging, trimming the flash and calibration

The typical sequence of forging operations includes 3 actions:

- Preforming when material doesn't flow in flash gutter;
- Finish forging with intensive flow material in flash and then trimming of the flash;
- Calibration in the final dies.

For the blades having small swirl angle less than 40 degrees the preforming blow is quite often done in the same finish dies. The deformation is just split between two blows and only 20-40% of the deformation is realized at the second action.

For the blades with big swirl angle that is more than 40° (see **Figure 2)** it is necessary to develop special preforming dies**.**

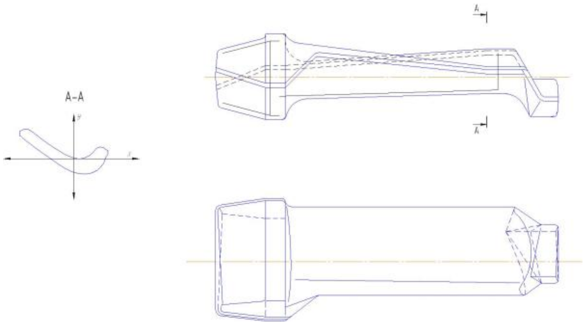


Figure 2. The drawing of the blade with 40° swirl angle.

Forging operations for producing the blades with bigger swirl angle from 40° to 85° are characterized by considerable shearing forces between upper and lower dies. This causes unbalance in material flow, low accuracy of dimensions and uneven distribution of excess material along the blade body as shown in **Figure 3**. Here despite of initially central positioning of the billet the flash is very uneven due to shifting the material towards one side.

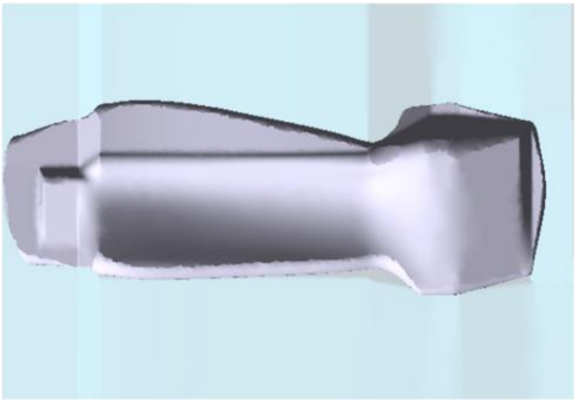


Figure 3. Preforming with unbalanced material flow that causes big contact pressure and short tool life and uneven flash.

The solution of the problem of unbalanced material flow in blade forging has been found by introducing a new design of the preforming dies that provides correspondence of preforming and finish die from the point of view of the die curvature orientation and compatibility.

The optimization of the material flow for preforming was realized by simulation of the material flow in different cross-sections of the blade body using program QForm. New orientation of cross sections of the blade body has been found by implementation of experience of the technologists and die designer and verifying the effectiveness of each variant by simulation.

The drawing of the preform part is improved to provide the balanced position of the workpiece during preforming operation. The blade cross sections are rotated with respect to each other along the axis of forging as, for example, is depicted for one of them in **Figure 4.**

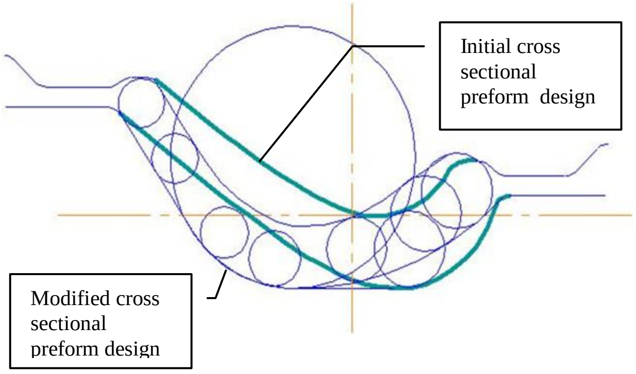


Figure 4. New die design provides balanced material flow in preforming operation. The peak load was reduced from 16MN to 8.5 MN.

After improvement of the die design in every cross-section it was verified by simulation of the material flow by QForm2D/3D to estimate the load reduction and how even is the material flow. The results some of the cross sections are shown in **Figure 5.**

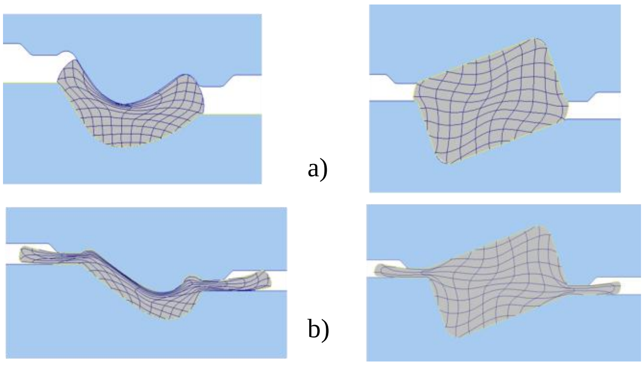


Figure 5. Material flow in preforming (a) and finish (b) operations with optimized die design. On the left are the sections across the blade body; on the right are the sections across the lock part of the die.

New die design provides well balanced material flow in preforming operation that reduces the peak of load from 16MN to 8.5 MN.

The peak load in finish forging operation is considerably bigger comparing to preforming blow that applies the total load limit to the whole technology. To overcome this problem the finish operation has been split into two actions with intermediate trimming of the flash in between. By these means the peak load has been reduced from 45 MN to 25 MN in the additional preforming blow and to 30 MN in the finish blow after intermediate trimming of the flash. The intermediate shape that provides the most even distribution of the load between last two blows has been found by means of the simulation. The sequence of the intermediate blade configurations after optimization is shown in **Figure 6**. Achieved load reduction considerably reduces possibility of premature die failure due to overload while it still may fail due to other reasons.

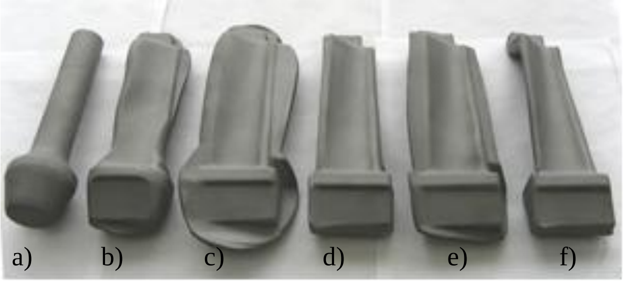


Figure 6. Head upsetting (a), preforming (b), second preforming (c), flash trimming (d), finish forging (e), trimming and calibration (f)

Another possible reason of short tool life during hot blade forging is intensive abrasive die wear. It depends on relative velocity of the material flow along the die surface, hardness and quality of the die material and temperature of the die during the forging process. Material flow optimisation described above provided considerable improvement of the tool life for preforming dies that now serve up to 1000 parts. At the same the dies in finish operation reach critical depth of abrasive wear after forging of just 300 pieces. Intensive die wear is clearly seen around flash area (**Figure 7)**.

Figure 7. The lower finish die with the trace of intensive abrasive wear after forging of 300 parts.

To improve resistance to abrasive wear the dies have been subjected to electric sparking alloying (ESA). ESA provides coating of the die surface by an alloyed layer with thickness up to several millimeters. ESA considerably changes mechanical, physical and chemical properties of the treated surface and also provides the possibility to cover the die cavity with solid lubricant such as graphite [1].

Figure 8 shows the microstructure of the die surface made of steel H13 that has been modified by ESA with tungsten alloy and graphite electrode. Metallography investigation has been done by microscope model MIM-10. The purpose of investigation was to find real depth of alloyed layer and check local distribution of hardness by micro hardness meter PMT-3M. The thickness of the alloyed layer is 0.75-1.7 mm.

The surface treatment of the finishing dies by ESA method provided the increasing of the tool life by several times up to 1000 pieces. The practice shows the shorter tool life for upper dies comparing to lower dies for blade forging. The tool life of the upper dies is about 600 pieces.

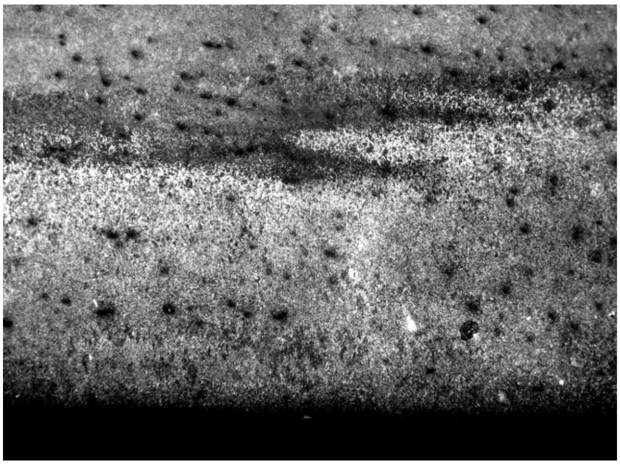


Figure 8. Microphoto with magnification x50 of modified surface of the die made of H13 steel alloyed by electrode made of tungsten alloy and graphite.

3. TEMPERATURE OF THE DIES AND FRACTURE

Even though reduction of the load due to optimisation of the material flow described above has reduced the risk of die cracks due to overloading, there are other possible measures that are necessary to undertake to ensure overall longer tool life. In cases when the die cracks it happens in the corners of the cavity where the bulk part of the blade is located as seen on the photo shown in **Figure 9**.

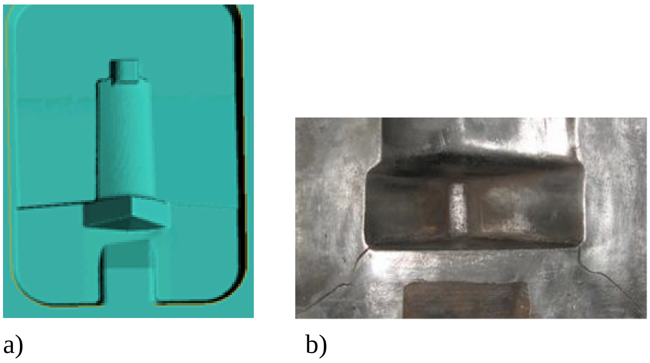


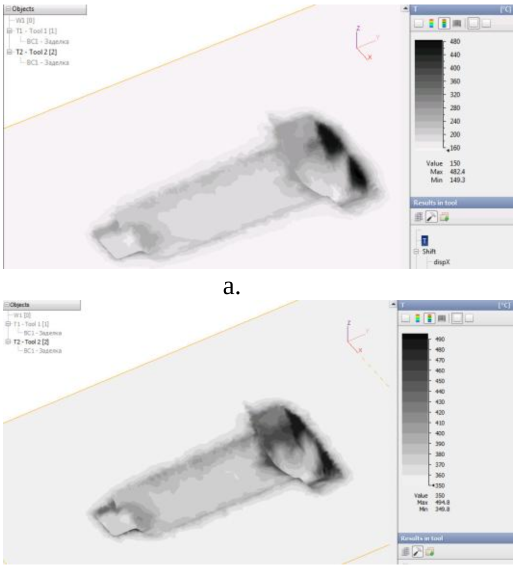
Figure 9. General view (a) and fracture of the die due to high tensile stress (b) that was preheated to 150-200°C

It was assumed that the die failure risk may be reduced further by providing condition for higher forging temperature. The initial heating temperature of the workpiece is 1200^{0}C and it cannot be heated to higher temperature due to material properties limitation. Meanwhile there is possibility to keep the temperature of the forged part higher by means of reducing the heat loss in it.

The die is heated in low-temperature electrical furnaces. The temperature of the dies is held during the technological pauses by the special heating equipment placed between lower and upper dies.

To check how the die temperature may influence the temperature of the forged part and in turn the peak load during finish forging we have done several simulations using the program QForm 7.0 that allows considering coupled analysis of thermo-mechanical problem in the workpiece and the dies [2].

The die temperature range for computational experiments has been set from 150^{0}C to 350^{0}C. It was found that initial die temperature significantly influences the temperature of the forged part meanwhile the temperature of the die itself at the end of forging blow varies very slightly. Some results of such simulation of temperature in lower die at the end of blow are shown in **Figure 10.**



a.

b.

Figure 10. Temperature distribution on the die surface at the end of blow. Initial temperature of the die was: (a) 150^{0}C; (b) 350^{0}C.

It is interesting to notice that despite the quite big difference in initial temperature of the dies (from 150^{0}C to 350^{0}C) the difference between them at the end of blow is not more than 12^{0}C and is respectively 482^{0}C and 494^{0}C. The die stress simulation has proved the presence of the zone with high level of tensile stress as shown in **Figure 10** in the area of the die crack that is shown in **Figure 9, b**. Meanwhile the maximum mean stresses for increased heated die is smaller in 1.5 times than in the die heated up to 150^{0}C.

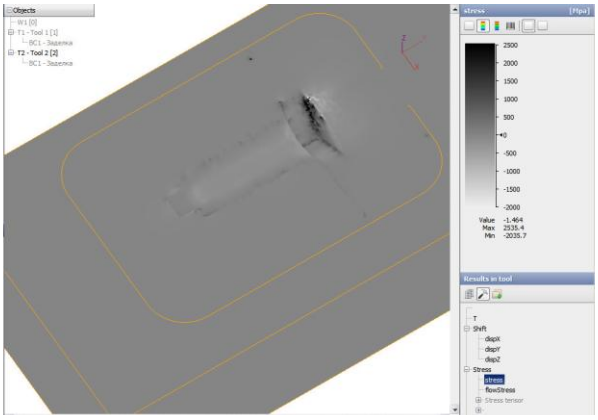


Figure 10. Tensile stress concentration in the zone of the die crack in the die preliminary heated up to 350^{0}C.

Such reduction of maximum tensile stress in the dies that have been preheated to higher temperature can be explained by lower contact stress that is the result of lower flow stress in the forged part. The reason is less heat loss to the workpiece material when it is in contact with hotter die surface.

The results obtained by numerical experiments have been tested in practically and have been completely proved. Due to alteration of the technology the tool life of both preforming and finish dies has been considerably extended and now the dies serve up to 1000 forged parts.

4. SUMMARY

Numerical and industrial investigation presented in this paper allowed us to get the following results:

- Optimisation of material flow in preforming operation of blade with 40^o swirl angle has provided balanced material flow and reduced the peak of load nearly twice from 16MN to 8.5 MN.
- Dividing the finish operation in two actions with intermediate flash trimming has provided the reduction of the peak of load in it from 45MN to 30 MN.
- Investigation by coupled analysis with QForm the forging operations has shown that increasing of the temperature of preliminary heating of the die from 150^{0}C to 350^{0}C does not cause big increasing of the temperature on the die surface at the end of blow but considerably reduces the tensile stress in the area of the die crack.
- Implementation of electric sparking alloying (ESA) for coating of the die surface has provided increasing of the abrasive resistance of the dies.
- All the results of investigation have been confirmed by practice.

5. REFERENCES

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