Some approaches on industrialization of steel thixoforging processes

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Abstract. Based on several years of research, this paper presents some approaches on industrializing steel thixoforging processes. From a billet to a complex-shaped final part obtained in one single step, several key elements of the forming process are developed, such as heating system, transfer system, part and die design. A series of key characteristics is listed to obtain a viable application to high frequency industrialization of thixoforged parts. This work demonstrates that it is possible to use a classical forming press, to implement an automatic transfer of the semi-solid slug and to thixoforge with a closed-die process. With a technological approach, a scientific topic is developed to identify generic parameters on thixoforged parts and lines.

Introduction

The Laboratoire de Conception, Fabrication et Contrôle of Arts et Métiers ParisTech, with its industrial and academic partners : Aubert and Duval, Aubervillers, Ascometal CREAS, Hagondange, Bourguignon and Barré, Hautes Rivières, Fives Celes, Lautenbach, CRITT MDTS, Charleville-Mézières, Courcelles ironworks, Nogent en Bassigny, the GRESPI of the University of Reims, have endeavoured to prove the feasability of the industrialization of the steel forming process of thixoforging in the semi-solid state. This work, based on several years of scientific research and know-how accumulated by Arts et Métiers ParisTech on the behaviour and modelling of semi-solid materials [1-5], as well as the identification of key parameters in the forming of metal alloys in the semi-solid state : low-melting point alloys [1-5] and steels [5, 6].

This work presents the forming of a C38LTT type steel part [7] whose complex shape was obtained on a high frequency industrial line.

Reference scientific data

The effects of various parameters of the steel forming process in the semi-solid state have already been studied in previous works [8]. The LCFC of Arts et Métiers ParisTech in Metz thus devised a specific die to reduce the diameter of steel in the semi-solid state by thixoforging. This technique allows a constant speed forming while integrating an induction heating device so as to remove slug heat losses during transfer and a resistive heating device to heat the Inconel© die [6].This experimental setup installed on a high frequency hydraulic press allowed to control and adapt the following parameters:

i. forming speed (from 30mm/s to 250mm/s)

ii. initial slug temperature (1429°C to 1450°C)

iii. die temperature (20°C to 400°C)

iv. forming stroke

The experiments were carried out under different settings on C38 steel billets, table 1.

The melting point of C38 steel is 1405°C and the end of fusion 1520°C, figure 1.

Table 1: Chemical composition of C38 low carbon steel (wt 10^{-3}%).

C	**Mn**	**P**	**S**	**Si**	**Al**	**N**	**Ni**	**Cr**	**Cu**
0.418	0.751	0.010	0.021	0.198	0.021	0.065	0.077	0.144	0.133

The maximum discrepancies in results between different experiments performed under the same conditions are of the order of 10 %. The study shows the importance of part/die thermal exchanges influencing the flow of matter and the evolution of microstructure during thixoforging process. The following results (table 2) are at the heart of the definition of a thixoforged part production line:

- Forming load decreases when die speed and slug temperature increase.

- Flow quality is clearly improved when die temperature increases (especially in the case of high slug temperature).

Table 2: Influence of speed, slug temperature and die temperature on steel thixoforging characteristics [9].

	Die speed. [mm/s]	Die Temp. [°C]	Slug Temp [°C]	Load [kN]	Flow	
Different **slug temperatures**	200	Cold	**1450 ↗**	**85 ↘**	1 Bad	
			1445	135	2 Bad	
			1429	190	**3 Good**	
Different **speeds**	40	Cold	1429	320	4 Good	
	200 ↗			**190 ↘**	5 **Good**	
Different **die temperatures**	200	Cold	1447	120	6 Bad	
		Hot ↗		**90 ↘**	7 **Good**	

The simultaneous increase of forming speed and initial die temperature reduces the impact of thermal exchange during thixoforging. Forming speed determines die/slug contact time and die temperature determines the heat flow at the die/slug interface. Temperature gradients at the part skin are greatly reduced, as the volume of matter remaining in the semi-solid state is still predominant. The decrease in the extrusion load with forming speed is due to the thixotropic property of steel in the semi-solid state and the decrease in heat losses.

During the industrialization, in order to get a quality part for a minimized forming load, it is preferable to thixoforge at high speed and with a heated die while adapting the slug temperature to avoid any ejection phenomenon.

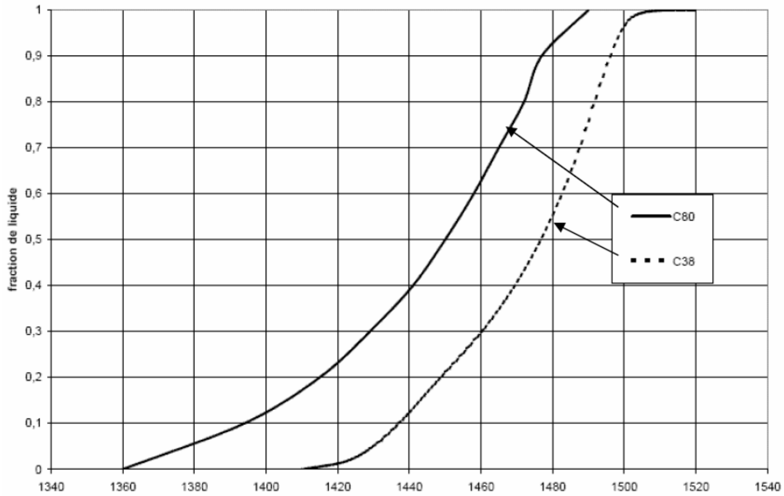

Figure 1: Measured fraction liquid curve for C38 Steel.

Means to implement for the industrialization of thixoforging

In order to implement the industrialization of high-melting point alloys in the semi-solid state by thixoforging, it is necessary to take into account the results previously presented. But that is not enough, as this knowledge has to be coupled with industrial constraints and, more importantly, to economic requirements. A minimum frequency of 10s per part is therefore recommended with a closed-matrix die design so as to control matter flow. The heating devices have been adapted to the slug's weight and to the matching frequency, while guaranteeing the heating temperature and above all the robustness of the heating. Indeed, the proposed heating system allows a variable load without affecting the quality of the heating by using only one power generator. In order to ensure a constant transfer time, a multi-articulated robot is inserted between the heating devices and the mechanical press.

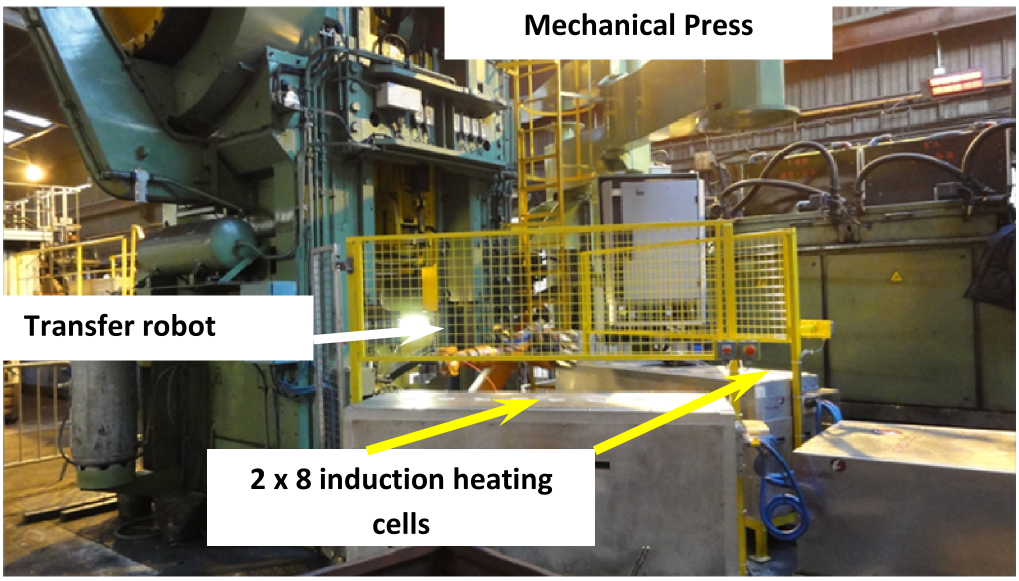

Figure 2: Industrial forming setup by thixoforging located at Bourguignon and Barré, consisting of a mechanical press, 16 induction heating cells and a transfer robot.

Part geometry and mechanical quality

The whole point of thixoforging is to make complex-shaped parts while reducing the number of forming steps (sometimes down to one single step) to obtain a Near-Netshape part [10-12]. Thixoforging enables to produce parts of a mechanical quality that can reach similar levels as in forged parts [10, 13, 14]. It is certainly superior to that of parts obtained by molding because of the grain flow and refinement, while allowing just as complex shapes. Below, in figure 3, is a C38 steel part, weighing 740g and measuring 35mm in diameter. It is representative of the shapes that can be achieved and illustrates several constraints: direct extrusion, indirect extrusion, radial extrusion, thin walls and asymmetrical geometry.

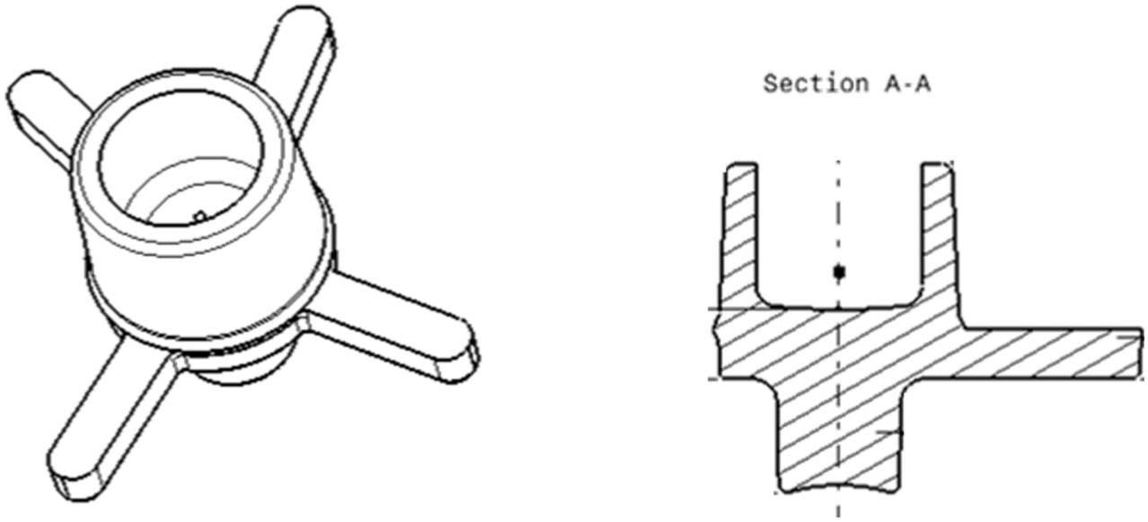

Figure 3: Schematic of the complex shaped asymmetrical part obtained by thixoforging.

Forming means

So as to meet the criteria of thixoforging, the press has to allow for a reduced forming time. For this work, a classic press technology was implemented to show the industrial feasibility of using a BRET-type exocentric mechanical press. The part is here obtained in one single step with a maximum load of 450KN depending on the heating conditions.

The dies are made from materials usually used by the forging industry. The part (figure 3 and 4) is produced in a X38CrMoV5 steel closed die. The forming process is complemented by lubrication and matrix heating as advised in several previous works [6]. The dies are also pre-heated at an initial temperature of 150°C.

Slug heating mode

Different studies have shown that induction heating is a good solution [15]. The induction heating of a C38 steel slug takes approximately 100s to reach 1430°C, which is incompatible with the expected minimum industrial speed of a part every 10s. In order to guarantee the producing of a part under industrial conditions, 16 heating cells (figure 2) are set up in series and heat the slugs under 160s each, for a global installation power of 600KW.

Heating cycles are controlled for each cell and for several configurations. S-type thermocouples are placed in test slugs to validate a temperature gradient of +/- 8°C at the end of a cycle for each cell.

To reduce carbon deposits on slugs before forming, heating cells work in a controlled atmosphere.

Transfer

So as to limit and control slug heat losses during its transfer under the press, a robot is placed to ensure that the distance between the press and the various cells is as short and as regular as possible. The transfer time is thus quasi-constant for each cell. The temperature of the thixoforged part remains identical whatever the slug's original cell.

Results

The industrial setup installed to thixoforge the part allowed to produce campaigns of over 6000 parts non-stop at a rate of 6 to 7 parts per minute. The parts obtained are very good quality (figure 4). Some early mechanical studies show very satisfactory characteristics and metallic structures for a C38. The average limit strength is 975 N/mm^2, the notch impact strength at room temperature is 10,6 J/cm^2 and the hardness is about 310 HV.

Figure 4: Thixoforged part at 1460°C in a heated die.

The first die produced more than 1000 parts, under constraining forming conditions, and, after control, wasn't showing any signs of premature wear. The die does not wear any quicker than closed dies used in heat forging. Several thixoforging campaigns have been planned to confirm these results.

Conclusion

With a rigorous adjusting of industrial devices and different forming parameters, it is now possible to form steels in the semi-solid state so as to meet the requirements and specifications of industrials specializing in forming. The industrial setup installed to thixoforge the C38 part (figure 4) has shown it is possible to produce a large number of parts with die speeds and wear compatible with economic and industrial constraints.

The potential of thixoforging must be used to devise and develop new products. The redesigning of combustion engine pistons illustrates the advantages of this technique.

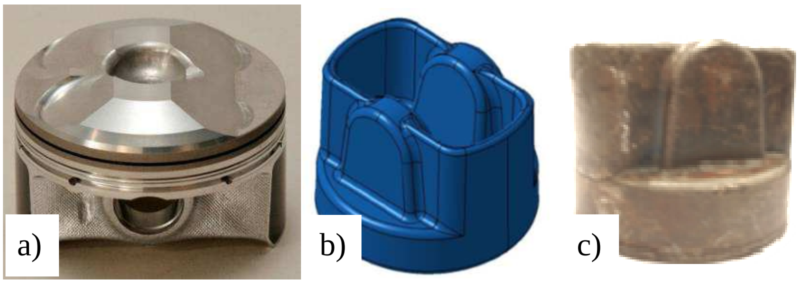

Figure 5 : a) Mazda Skyactiv-G engine piston, b) and c) C45 steel piston, designed and thixoforged at Arts et Métiers, [16].

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