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Research Paper

Experimental investigation of the thixoforging of tubes of low-carbon steel

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ABSTRACT

This article presents the outcomes of using thixo-extrusion (backward and forward) to produce tubes in low-carbon steel, grade SAE1006 (C05). According to the literature data, the semisolid state of this steel, required for thixoforging, is very difficult to obtain and has never been studied for this type of shaping. The experimental tests involve using an inductive heating and a flashless forging process. This work shows the route and possibility to obtain a usable semisolid by inductive heating for thixoforging of this steel grade. It shows by simulation the validation steps before the shaping and the forming constraints. A geometrical analysis of the parts revealed the good dimensional performance of thixoforging processes with high repeatability and a good microstructure. Such thixoforged tubes extend the dimensional limits of the tube wall thickness, as compared to the case of conventional forging in one step and in the framework of a typical industrial installation. These results could be integrated into a knowledge management system of thixoforging to identify new possibility of components.

1. Introduction and context

Püttgen et al. (2007) said that metal alloys forming at the semisolid state appears to present economic and product earning opportunities by combining the advantages of forging and casting. Cézard and Sourmail (2008) made a presentation of the advantages (e.g., reducing the shaping cycle, forming energy, reduction required machining, and dimensional and geometric tolerances and enabling the formation of complex shapes and thin walls). The metal forming method presented in this article involves thixoforging, where a semisolid is obtained by partial melting with a reduced liquid fraction below 20%. But Püttgen et al. (2007) defined this shaping zone as between 10 and 25% of the liquid fraction. Previous studies have largely focused on alloys with relatively low melting temperatures and with easy heating conditions, where the liquid fraction of a semisolid is not highly sensitive to variations in temperature. The focus of such studies has also been limited to geometries meeting conventional forging forming criteria. For a more frequently use of thixoforging in the industry must do research to improve the knowledges of the field of application and the limits of this process in terms of possibilities of shaping materials, accessible geometries and product qualities, structural and mechanical.

Thixoforging of a tubular part is investigated in this paper. Unlike complex shapes, this geometry limits difficulties associated with analysing material flows and, in this case, the flow involves extrusion. This simple geometry enables investigations of more elementary material flows via forging tooling and the influences of the direction of shaping and forward and backward extrusion according to the tool used. It simultaneously allows constraints and specificities of forming related to the thixoforging, among others constraints, to be investigated. However, this simple a priori shape cannot be obtained easily through conventional forging because of certain dimensional and geometric requirements.

In the spirit of defining certain limits for the application of steel thixoforging, an SAE1006 low-carbon-percentage steel grade of steel was used and studied. It is noteworthy that the semisolid forging of such low-carbon steel grades was never studied in the literature. For a particular alloy grade to be used at the semisolid state for forming, knowledge of its melting and solidification kinetics enables the design of heating cycles to reach the semisolid state of the alloy to a targeted liquid fraction. Unfortunately, it is difficult to establish the melting and solidification kinetics accurately because the heating rates of the induction furnaces used for experiments are very high compared to that of differential scanning calorimeters usually used to determine the liquid fraction at a given temperature. The determinations of liquid-solid fraction curves as a function of temperature by differential thermal analysis (DTA) are typically carried out at low heating rates (from 20 to 50 °C per minute according to installations). Hirt et al. (2006) presents the DAT results for different steels grades generally studied in the literature. In contrast, induction heating methods conventionally applied for thixoforging range from 100 °C per minute to 900 °C per minute.

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Many authors have shown that the heating rate influences the liquid fraction evolution of an alloy and that there is no way to obtain a rigorous liquid fraction for large heating rates. Gu et al. (2015, 2014) had studied the liquid fraction evolution at high heating speeds but for specific steel grades such as M2 that are not commonly used in the forging industry. At a solid state, the carbides of M2 steel are visible and correspond on a percentage basis to the liquid fraction of the semisolid alloy. Therefore, for the remainder of this article, given current difficulties associated with accurately determining the liquid fraction, only the heating temperature of the billet and its steel grade are given and the liquid fraction is evoked in an indicative manner. The reader can easily note that thixoforging is performed at a liquid fraction of less than 20% according to DTA curves, corresponding to numerous guidelines listed in the literature. Hirt et al. (2006) showed that shaping by thixoforging should be carried out at liquid fractions between 10 and 20%, whereas Cézard (2006) and Becker (2008) obtained good-quality parts using liquid fractions of less than 10%, as was the case for the Thixofranc project (Bigot et al., 2013).

According to the kinetics of solidification, the use of low-carbon steel is not favourable for thixoforging. Furthermore, as others Cézard (2006), Winship (1978), Fischer (2008) and Lozares et al. (2014) have shown, a lower carbon content results in a higher temperature of the semisolid domain of metal alloys and in a lower difference between the temperature of the solid and that of the liquid. Certain addition elements, even in small amounts, can improve the heating conditions of an alloy. Alloy modification patents demonstrating the improvement of the thixoforging of a steel grade have been established (2004). Rassili and Atkinson (2010) compares the C38 and C38LTT DAT this last one specially designed for shaping of semisolid state.SAE1006 steel has a low carbon content and includes no specific elements that can decrease the melting temperature and/or increase the temperature range between the solid phase and liquid phase, which means that for small variations in temperature, variations of the liquid fraction can be large, rendering the control of heating to obtain a precise liquid fraction difficult. Table 1 presents the melting temperature and temperature difference between the solid and liquid phase for SAE1006 steel compared to various steel grades used in research related to the shaping of steels in the semisolid state.

Some steel grades have temperature ranges between solidus and liquidus that are larger than others, making it easier to control a liquid fraction using a heating system. However, because of their characteristics, these steels often cannot be applied to forged parts. Tube thixoextrusion is expected to help defining the process windows and limitations for the thixoforging of steel grades with narrow solidus-liquidus temperature range.

This paper presents experimental test results on a low-carbon and low-alloy steel grade that is difficult to use for thixoforging. According to specific forming conditions, this approach makes it possible to

- validate the use of SAE1006 steel for thixoforging,
- validate dimensional and geometric conditions difficult to achieve via conventional forging,
- check the material flow and its macrostructure and microstructure.

2. Selection of tube design, materials and processes

2.1. Tube design and material

This part obtained by thixoextrusion has been described by various authors. Hirt et al. (2005) used this process to shape in the semisolid state via the rheoforging of 100C6 stainless steel.

To study the effects of material flows on of thixoforging results, we

Table 1

Comparison of the solidus-liquidus domain and the melting start temperatures of different steels (Omar et al. 2005; Yi et al. 2012; Rassili et al., 2006; Cezard et al., 2007b; Becker, 2008; Lozares et al., 2014; Cézard, 2006; Kopp et al., 2002; Omar et al., 2011; Gu et al., 2012; Mohammed et al., 2013; Hirt et al., 2005).

Steel Grade		Carbon percentage in steel (Mass %)	Melting start temperature (°C)	End of melting temperature (°C)	Temperature difference between solidus and liquidus (°C)
SAE1006		0.05	1456	1519	63
HP9/4/30 (Omar et al., n.d.)	Increased carbon percentage ↓	0.31	1430	1490	60
SKD61 (Yi et al., 2012)		0.36	1318	1489	171
C38 (Rassili et al., 2006)		0.38	1430	1530	100
C38 LTT (Rassili et al., 2006) (Cezard et al., 2007b) (Becker, 2008)		0.38	1380	1500	120
C45 LTT (Lozares et al., 2014)		0.45	1360	1475	115
C80 (P. Cézard, 2006)		0.8	1360	1485	125
M2 (Kopp et al., 2002) (Omar et al., 2011) (Gu et al., 2012)		0.85	1230	1455	225
100C6 (P. Cézard, 2006)		1	1275	1445	170
X210CrW12 (Mohammed et al., 2013) (Hirt et al., 2005)		2.1	1215	1405	190