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A new experimental method for identifying the conditions necessary for diffusion bonding in free cutting steels

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ABSTRACT

Porosity in cast bloom steel may lead to reduced strength or inconsistency of final rolled bar products and components if not properly closed and healed during the hot rolling process. Partial or complete recovery of strength in such porous materials can be achieved by diffusive healing processes at elevated temperatures. Devising an appropriate healing process that does not cause discontinuity in the microstructure, and in the mechanical properties at the bonding sites, whilst preventing distortion of the component during bonding requires an accurate choice of thermo-mechanical processing parameters. Despite work carried out on optimising diffusion bonding in materials such as titanium alloys, aluminium alloys and copper, the diffusion bonding process in free cutting steels has received relatively little attention. To support thermomechanical process optimisation (e.g. rolling) and calibration of theoretical models, a new experimental method was developed to determine combinations of load, temperature and time sufficient for complete diffusion bonding in as-cast Free Cutting Steels (FCS). The extent of diffusive healing and bond strength were examined by tensile testing to failure corroborated by SEM examination of the bond line. This enabled optimal loading conditions for the formation of a complete, strong bond to be identified.

1. Introduction

Continuous casting is used to solidify most of the 750 million tons of steel produced in the world every year [1]. The process reduces the number of required milling stages and results in semi-finished products such as billets, blooms and slabs which will later be rolled into more specific shapes and finished products (e.g. bars, rods, plates, etc.). Extending the range of finished product sizes produced from a given concast bloom or billet section is often limited by the minimum area reduction required to ensure effective central consolidation and final mechanical properties. Porosity in as-casts billets could be caused by factors such as entrained air during filling, solidification shrinkage, mould wall reactions and dissolved gases [2]. Predicting effective consolidation or level of remnant porosity for a range of steel grade (function of solidification regime), billet size, pass schedule/roll design and thermo-mechanical conditions has always been an important issue for steel producers as it will affect the mechanical properties of final products (strength, ductility, etc.) [3]. It is known that partial or complete recovery of strength in such porous materials can be obtained by pore closure and diffusive healing processes at elevated temperatures.

Healing by reducing material defects such as voids and cracks to the point where diffusive bonding may occur, resulting in a stiffer and stronger material with enhanced mechanical properties, has been studied for many material applications. This method of healing has proven very successful in applications involving polymers and composites [4,5], biomaterials [6,7] and also for recovery of concrete [8,9]. Metal healing has been mostly studied in terms of sinter powder metallurgy where mass transfer of metal occurs at high temperatures in the range of 0.7–0.9 of the melting temperature, producing either solid state or liquid phase bonding across powder interfaces [10].

Void healing has been studied as the final stage of crack healing [11,12] and metal bonding [13,14]. In crack healing, pore formation is due to crack splitting, whereas in metal bonding, voids form as a result of contact and deformation of surface asperities. There have been many attempts to model the void shrinkage process; however these models use different approaches. Derby and Wallach [13] developed a mathematical model for the bonding process (elimination of bond interface voids of cylindrical shape), predicting the overall bonding rate and also the dominant mechanisms as bonding progresses. They studied the diffusion bonding of copper experimentally, where the extent of bonding was determined using optical microscopy, and the results were compared with the predictions of their model. Later Guo and Ridley used the same approach to develop a mathematical model for elimination of bond interface voids of irregular shapes [14]. They used the experimental data from Derby and Wallach to validate their model. The optimal conditions to create high quality diffusion bonds have already been reported for some titanium alloys, aluminium alloys and magnesium alloys [15–17].

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To improve the efficacy of the void healing process and calibrate diffusion bonding models for free cutting steels, it is essential to identify the conditions that lead to complete diffusion bonding. The main factors affecting the quality of the bonds are temperature, pressure and time. The effect of these parameters on damage recovery has been investigated experimentally by Han et al. [18] on crack recovery in 20MnMo steel, which indicated that damage recovery could be achieved without plastic deformation, just by increasing the temperature and prolonging the holding time. However, another experimental study on crack healing in 1045 steel showed that even after a 120 min heat treatment at 1100 °C, micro-voids were left in the crack healing area [19]. It is well known that void closure is more easily and quickly obtained if plastic deformation takes place under the influence of compressive hydrostatic pressure [20]. Wang et al. [21] found that pore closure occurs at a certain level of hydrostatic pressure and accelerates at high temperatures. It was also shown that the holding period of the pressure in the compressive state affects the degree of healing, together with the state of oxidation in the vicinity of the porosity.

Although void closure and healing have been widely studied for different alloys, the conditions required to create self-bonding of FCS cast steel porosity has never been investigated, and is the main focus of this paper. It is also noteworthy that in the majority of studies on diffusion bonding, an examination of the bond strength has not been carried out. In most cases SEM and optical microscopy have been used, focusing on observation of the bonding line. The approach described in this study offers a way of identifying combinations of load, temperature and time that lead to complete diffusion bonding by testing the mechanical strength of the resulting bond. SEM analysis has also been used to corroborate the mechanical testing by examining the extent of healing at the bond line.

The optimal conditions for diffusion bonding with respect to the requirements of a thermomechanical processing method (e.g. rolling) were identified from those that led to complete diffusion bonding in the experiments; load applied in rolling is linked to the cross sectional area reduction, and a higher rolling speed increases efficiency and output, hence it is desirable to reduce both the load and time required for complete bonding at a given temperature whilst ensuring a strong bond is formed.

A secondary aim of this work was to provide a test method that can be used for calibration of void elimination models, such as that presented in [22], based on void closure according to Gurson–Tvergaard porous plasticity, and healing by creep and diffusion according to the Pilling model of diffusion bonding [23].

2. Experiments

2.1. Material and specimens

Cylindrical samples manufactured from as-cast FCS billets by TATA Steel were used for the experimental investigation. The samples were cut from the non-porous section of the billet (billet surface). The composition of the material is shown in Table 1.

The specimens were machined into cylinders having 10 mm diameter and 111 mm length with threaded ends. The cylinders were then cut in half (see Fig. 1), producing two 55.5 mm long cylindrical samples, threaded at only one end. The cut surfaces were ground to a smooth surface finish, with roughness no greater than 9.1 μm, finishing with P2500 abrasive paper.

2.2. Bonding procedure

The test procedure comprised compressing the two halves of each specimen, which were put back together such that their axes were aligned, under various combinations of load and time at a given temperature. The load and the holding time were varied in a systematic way to ensure that accurate estimations of the required load and healing time were obtained. The specimens were subsequently tested in tension to assess the extent of the healing process by inspecting the resulting flow curves.

The tests were conducted using a Gleeble 3800, which is a fully integrated digital closed-loop control thermal and mechanical testing system. Desired temperatures were achieved by direct resistance heating, with temperature at the bond line measured and controlled using thermocouples. To ensure the same temperature was achieved on both sides of the bond line, thermocouples were welded at a distance of 2.5 mm on either side of the bond, and their readings were maintained within 20 °C throughout the tests.

The Gleeble was operated under load control with copper grips. The direct resistance heating mechanism of the Gleeble requires sufficient initial contact between the two halves of the specimen. To achieve this, the specimens were preloaded. It was found that an applied load of -0.5 kN, corresponding to a pressure of 6.4 MPa for a 10 mm diameter sample, maintained for a minimum of 30 s produced the contact conditions necessary to achieve a temperature of 1000 °C by direct resistance heating. The 30 s preloading time also served as a soaking period to achieve a uniform temperature along the gauge of the specimen. Following the preloading step, the force was increased until one of three target values was reached, and the specimens were held at that load for varying time periods. In all cases the loading rate was adjusted by the control system such that a constant strain rate of 0.01 s^{-1} was maintained. Since the sample temperature was uniform, cases where the applied load divided by the original cross sectional area (nominal stress) was in excess of the yield stress incurred plastic deformation of the entire sample gauge and associated barrelling.

Table 1
Chemical composition of leaded free cutting steel (LFCS).

Element	C	Si	Mn	P	S	Other(Pb)
% Weight	0.07	0.01	1.00	0.05	0.30	< 0.40

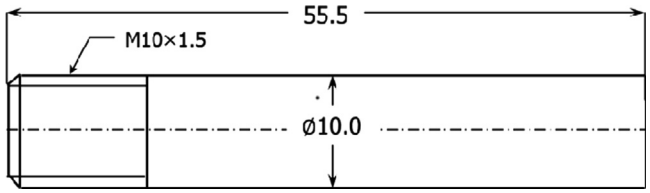

Fig. 1. Test specimen dimensions (mm).

Table 2
The load-time combinations tested for 1000 °C.

Test no.	Load (kN)	Nominal pressure (MPa)	Time
1	1.0	12.7 ($\approx 0.4\sigma_y$)	2.5 min
2	1.0	12.7 ($\approx 0.4\sigma_y$)	4 min
3	1.0	12.7 ($\approx 0.4\sigma_y$)	5 min
4	1.0	12.7 ($\approx 0.4\sigma_y$)	10 min
5	3.0	38.2 ($\approx 1.3\sigma_y$)	20 s
6	3.0	38.2 ($\approx 1.3\sigma_y$)	30 s
7	3.0	38.2 ($\approx 1.3\sigma_y$)	1 min
8	3.0	38.2 ($\approx 1.3\sigma_y$)	2 min
9	5.0	63.7 ($\approx 2.1\sigma_y$)	10 s
10	5.0	63.7 ($\approx 2.1\sigma_y$)	20 s
11	5.0	63.7 ($\approx 2.1\sigma_y$)	30 s
12	5.0	63.7 ($\approx 2.1\sigma_y$)	1 min